

An Efficient MAC Protocol with Selective Grouping and Cooperative Sensing in Cognitive Radio Networks

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Abstract—In cognitive radio networks, spectrum sensing is a crucial technique to discover spectrum opportunities for the Secondary Users (SUs). The quality of spectrum sensing is evaluated by both sensing accuracy and sensing efficiency. Here, sensing accuracy is represented by the false alarm probability and the detection probability while sensing efficiency is represented by the sensing overhead and network throughput. In this paper, we propose a group-based cooperative Medium Access Control (MAC) protocol called GC-MAC, which addresses the tradeoff between sensing accuracy and efficiency. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel while SUs in the same team perform the joint detection on the targeted channel. The sensing process will not stop unless an available channel is discovered. To reduce the sensing overhead, an SU-selecting algorithm is presented to selectively choose the cooperative SUs based on the channel dynamics and usage patterns. Then, an analytical model is built to study the sensing accuracy-efficiency tradeoff under two types of channel conditions: time-invariant channel and time-varying channel. An optimization problem that maximizes achievable throughput is formulated to optimize the important design parameters. Both saturation and non-saturation situations are investigated with respect to throughput and sensing overhead. Simulation results indicate that the proposed protocol is able to significantly decrease sensing overhead and increase network throughput with guaranteed sensing accuracy.

Index Terms—Cognitive MAC, spectrum sensing, sensing accuracy, sensing efficiency.

I. INTRODUCTION

Recently, the explosive increase of wireless devices and applications poses a serious problem of compelling need of numerous radio spectrum. The problem is greatly caused by the current fixed frequency allocation policy, which allocates a fixed frequency band to a specific wireless system. On the contrary, a recent report published by the Federal

Communication Commission (FCC) reveals that most of the licensed spectrum is rarely utilized continuously across time and space [1]. In order to address the spectrum scarcity and the spectrum under-utilization, Cognitive Radio (CR) has been proposed to effectively utilize the spectrum [2]–[4]. In the CR networks, the Secondary (unlicensed) Users (SUs) are allowed to opportunistically operate in the frequency bands originally allocated to the Primary (licensed) Users (PUs) when the bands are not occupied by PUs. SUs are capable to sense unused bands and adjust transmission parameters accordingly, which makes CR an excellent candidate technology for improving spectrum utilization.

Spectrum sensing is a fundamental technology for SUs to efficiently and accurately detect PUs in order to avoid the interference to primary networks. However, in CR networks, many unreliable conditions [6]–[8], such as channel uncertainty, noise uncertainty and no knowledge of primary signals, will degrade the performance of spectrum sensing. Cooperative sensing [9]–[15], has been studied extensively as a promising alternative to improve sensing performance at both of the physical (PHY) level and the medium access control (MAC) level. The main interest of this paper is the cooperative sensing mechanism at the MAC level, which performs sensing operations in two aspects: 1) assign multiple SUs to sense a single channel for improving the sensing accuracy; 2) assign cooperative SUs to search for available spectrums in parallel to enhance sensing efficiency.

The improvement of sensing accuracy is extensively treated in [10]–[12]. The study in [10] reports a cooperative sensing approach through multi-user cooperation and evaluates the sensing accuracy. The authors of [11] consider cooperative sensing by using a counting rule and derive optimal strategies under both the Neyman-Pearson criterion and the Bayesian criterion. The study in [12] presents a new cooperative wide-band spectrum sensing scheme that exploits the spatial diversity among multiple SUs which also contributes to improve the sensing accuracy. These studies have mainly focused on improving sensing accuracy while sensing efficiency has been ignored. The enhancement for sensing efficiency has been investigated in [13][14]. The study in [13] introduces an opportunistic multi-channel MAC protocol which integrate two novel cooperative sensing mechanisms, i.e., random sensing policy and negotiation-based sensing policy. The latter strategy assigns SUs to collaboratively sense different channels to improve the sensing efficiency. For the sake of reducing

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sensing overhead, the authors of [14] propose a multi-channel cooperative sensing scheme, where the cooperative SUs are optimally selected to sense the distinct channels at the same time for sensing efficiency. These works assume that the sensing accuracy of one channel by a single SU is completely true which is may not be practical in real communication systems.

In addition, literatures above did not consider the design of the cooperative MAC protocol for distributed networks and perform theoretical analysis of sensing overhead and throughput. Hence, we are interested in achieving both sensing accuracy and sensing efficiency by introducing a cooperation protocol in MAC layer for CR networks. Several cognitive MAC protocols have been proposed in the literature to address various issues in CR network [13][17][20]-[25]. However, these protocols do not leverage the benefit of cooperation at MAC layer for enhancing the sensing efficiency without degrading the sensing accuracy.

In this paper, we propose a group-based cooperative MAC protocol called GC-MAC. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel. The sensing process will not stop unless an available spectrum channel is discovered. The purpose of team division has twofold: 1) sensing a channel by several SUs for the improvement of sensing accuracy; 2) finding more spectrum opportunities by sensing distinct channels by different teams. As a consequence, multiple distinct channels can be simultaneously detected within one sensing period which leads to the enhancement of sensing efficiency.

To reduce the sensing overhead, we propose an SU-selecting algorithm for GC-MAC protocol. In the SU-selecting algorithm, we selectively choose the optimal number of the cooperative SUs for each team based on the channel occupation dynamics in order to substantially reduce sensing overhead. We analyze the sensing overhead and throughput in the saturation and no-saturation network cases, respectively. In the saturation networks, each SU always has data to transmit. In the non-saturation networks, an SU may have an empty queue. In every network case, we consider two types of channel conditions: time-invariant channel and time-varying channel. In each condition, the sensing overhead and the throughput are incorporated into an achievable throughput maximization problem, which is formulated to find the key design parameters: the number of the cooperative teams and the number of SUs in one team. Furthermore, we present extensive examples to demonstrate the sensing efficiency comparing with the existing schemes and to show the determination of the crucial parameters. Simulation results demonstrate that our proposed scheme is able to achieve substantially higher throughput and lower sensing overhead, comparing to existing mechanisms.

The remainder of this paper is organized as follows. In Section II, the system models are introduced. Section III reports our proposed group-based MAC protocols for cooperative CR network. Section IV introduces an SU-selecting algorithm for appropriately selecting the cooperative SUs so as to reduce the sensing overhead. Then, we study the sensing overhead and achievable throughput in the saturation and non-saturation networks in Section V and Section VI, respectively. Section

VII evaluates the performance of the proposed GC-MAC protocol based on our developed analytical models. Finally, we draw our conclusions in Section VIII.

II. SYSTEMS MODELS

A. Channel Usage Model

We assume that each licensed channel alternates between ON and OFF state, of which the OFF time is not used by PUs and hence can be exploited by the SUs. Assume that the durations of the ON and the OFF period are independently exponentially distributed. For a given licensed channel, the duration of ON period follows an exponentially distributed with parameter μ_{ON} and the duration of OFF period with an exponentially distributed parameter μ_{OFF} . We define the channel availability as the normalized period which is available for SUs. Let p denotes the channel availability. Then, we have $p = \frac{\mu_{ON}}{\mu_{OFF} + \mu_{ON}}$. Similar to [13], in this paper, we mainly consider that the licensed channels used by the same set of PUs, i.e., the licensed channel availability information sensed by each SUs is consistent among all SUs.

We consider two scenarios depending on the channel dynamics. The first is the time-invariant channel with unchanged channel data rate R . The throughput of the SU by using time-invariant channel only depends on the constant data rate and the valid transmission time T_r . The second type of channel is the Time-Varying Channel. The Finite-State Markov Channel (FSMC) model is employed to model the dynamics of the time-varying channel [19]. The dynamics of the time-varying channel is partitioned based on the channel data rate. It is reasonable to employ the channel data rate instead of Signal-to-Noise Ratio (SNR) which has been used in conventional FSMC model. Since the channel data rate is closely relevant to the application layer requirements and hence its usage facilitates the construction of resource demands from an application perspective. The set of the channel state is denoted as $\mathbf{M} \equiv \{1, 2, \dots, M\}$ with $|\mathbf{M}| = M$. Let c_i represents the channel state i ($i \in \mathbf{M}$). The state space is denoted as $\mathbf{S} \equiv \{c_i, i \in \mathbf{M}\}$. Let π_i ($i \in \mathbf{M}$) represents the steady-state probability at state c_i . Then, the steady-state probability can be solved using the similar technique in [19]. During data transmission within a frame, the time-variation is slow enough that the channel data rate does not change substantially. This assumption is acceptable due to the short data transmission period within a frame and has been frequently used, e.g. [18] [26].

B. Energy Detection Model

In order to discuss our problem, we employ Energy Detection [7] as the spectrum sensing scheme. Both of the real-valued signal model and the complex-valued signal model are used to describe the received signal at the SU's receiver.

1) *Real-Valued Signal Model*: Let t_s be the sensing time and f_s be the sample frequency during sensing time. We denotes N as the number of samples in a sensing period, i.e. $N = t_s f_s$. The received signal $r_k(n)$ at the n th sample and

the k th SU is given by,

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ s_k(n) + w_k(n), & H_1 \end{cases}$$

where H_0 represents the hypothesis that PUs are absent, and H_1 represents the hypothesis that PUs are present. $s_k(n)$ represents the PU's transmitted signal which is assumed as a real-valued Gaussian signal with mean zero and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with mean zero and variance σ_w^2 .

Let $e_k(r)$ denotes the test statistic of the k th SU. Then, we have $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false alarm probability of k th SU are given by,

$$P_d^k = \Pr[e_k(r) > \lambda | H_1], \quad P_f^k = \Pr[e_k(r) > \lambda | H_0]$$

where λ is a decision threshold of energy detector for a SU.

The test statistic $e(r)$ is known as Chi-square distribution with $\frac{e(r)}{\sigma_w^2} \sim \chi_N^2$ under hypothesis H_0 , and $\frac{e(r)}{\sigma_s^2 + \sigma_w^2} \sim \chi_N^2$ under hypothesis H_1 . However, if the number of samples is large, we can use the Central Limit Theorem (CLT) to approximate the Chi-square distribution by Gaussian distribution [7] under hypothesis $H_z (z = 0, 1)$ with mean μ_z and variance σ_z^2 as,

$$\begin{cases} \mu_0 = N\sigma_w^2, & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(\sigma_s^2 + \sigma_w^2), & \sigma_1^2 = 2N(\sigma_s^2 + \sigma_w^2)^2, & H_1. \end{cases}$$

Therefore, the probabilities P_d^k and P_f^k can be approximated in terms of the Q function is given by,

$$P_d^k = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{2N(\sigma_s^2 + \sigma_w^2)}}\right), \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^2}}\right)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{(-\frac{t^2}{2})} dt$.

2) *Complex-Valued Signal Model*: Considering the complex-valued signal model, the received signal $r_k(n)$ at the n th sample and the k th SU can be given by,

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ h_k s_k(n) + w_k(n), & H_1 \end{cases}$$

where the channel coefficients h_k is zero-mean, unit-variance complex Gaussian random variables. $s_k(n)$ represents the PU's transmitted signal which is assumed as a Gaussian signal with mean zero and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with mean zero and variance σ_w^2 .

The test statistic of the k th SU $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false alarm probability of k th SU are given by,

$$P_d^k = \Pr[e_k(r) > \lambda_c | H_1], \quad P_f^k = \Pr[e_k(r) > \lambda_c | H_0],$$

where λ_c is a decision threshold of energy detector for a single SU considering the complex-valued signal model. For a large N , the distribution of $e_k(r)$ can be approximated as Gaussian distribution [7] with mean μ_z and variance σ_z^2 under hypothesis $H_z (z = 0, 1)$ as,

$$\begin{cases} \mu_0 = N\sigma_w^2, & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(|h_k|^2 \sigma_s^2 + \sigma_w^2), & \sigma_1^2 = 2N(|h_k|^2 \sigma_s^2 + \sigma_w^2)^2, & H_1 \end{cases}$$

Finally, we can obtain the probabilities P_d^k and P_f^k in terms of the Q function as

$$P_d^k = Q\left(\frac{\lambda - N(|h_k|^2 \sigma_s^2 + \sigma_w^2)}{\sqrt{2N(|h_k|^2 \sigma_s^2 + \sigma_w^2)}}\right), \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^2}}\right),$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{(-\frac{t^2}{2})} dt$.

C. Counting Rule

In order to improve sensing performance, an efficient fusion rule is needed to make final decision to the availability of the channel. Depending on every SUs' individual decision from one team, there are three popular fusion rules: And-rule, OR-rule and Majority-rule [18]. And-rule mainly focuses on maximizing the discovery of spectrum opportunities which are deemed to be exist if only one decision says there is no PU. In OR-rule, as far as limit the interference to the PU, the spectrum is assumed to be available only when all the reporting decisions declare that no PU is present. The last Majority-rule is based on majority of the individual decisions. If more than half of the decisions declare the appearance of primary user, then the final decision claims that there is a primary user. Without loss of generality, we use the Majority-rule in this paper with the assumption that all the individual decisions are independent, and supposing that $P_d^k = P_d$ and $P_f^k = P_f$ [18]. Then the joint detection probability and false alarm probability by j number of SUs are given by

$$P_d(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_d)^{j-\lceil \frac{j}{2} \rceil - y} P_d^{\lceil \frac{j}{2} \rceil + y}, \quad (1)$$

$$P_f(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_f)^{j-\lceil \frac{j}{2} \rceil - y} P_f^{\lceil \frac{j}{2} \rceil + y}. \quad (2)$$

III. GC-MAC: GROUP-BASED COOPERATIVE MAC PROTOCOL

In this section, we present the specifications of the proposed MAC protocol, together with the group-based cooperative spectrum sensing scheme and the SU-selecting algorithm. To describe our protocol conveniently, we have the following assumptions:

- Each SU is equipped with a single antenna which can not operate the sensing and transmission at the same time. According to this constraint, the sensing overhead caused by sensing is unavoidable and cannot be neglected in protocol design.
- A common control channel is available for all SUs to communicate at any time.
- An SUs can be assigned to perform cooperative sensing even when they have the packets to transmit.

A time frame of the secondary network operation is divided to three phases: reservation, sensing and transmission. All SUs are categorized into three types:

- Source SU (SU_s): an SU that has data to transmit.

- Cooperative SUs (SU_c): SUs that are selected for cooperative sensing.
- Destination SU (SU_d): an SU that receives the data packet from the source SU.

A. Reservation

In GC-MAC, any SU_s entering the network first try to perform a handshake with SU_d on the control channel to reserve a data channel. This allows the SU_s and SU_d to switch to the chosen channel for data transmission. Here, we use R-RTS/R-CTS packets for SU_s and SU_d to compete the data channel with other SUs. The SU_s will listen to control channel for a time interval T . If no R-RTS/R-CTS is received or time T is expired, the SU_s participates in the reservation process. Otherwise, it will defer and wait for the notification from the transmission pair or a timeout. Whenever there is at least one packet buffered in the queue, SU_s sends reservation requirement to SU_d . Upon receiving the requirement, SU_d will reply and other SUs overhearing these message exchanging cease their own sensing, and wait for the notification from this transmission pair or a timer expiration. When the sensing or cooperative sensing is finished, other neighboring SUs start a new round of competition for the control channel with a random backoff.

B. Sensing

After reserving the data channel, SU_s and SU_d start to sense the spectrum channel. In this phase, we use S-RTS/S-CTS packets for spectrum sensing and negotiation between SU_s and SU_d . In order to indicate the mechanism of our scheme, the C-RTS/C-CTS packets are included in the RTS/CTS model for SU_c to acknowledge its participation. Fig. 1 shows the flowchart of the sensing procedure of the source node SU_s . Fig. 2 shows the flowchart of the sensing procedures of SU_c and SU_d . In particular, we provide the detailed description as follows.

Source SU (SU_s)

- 1) SU_s senses the channel to judge the availability of the channel. If the channel is not occupied by a PU, SU_s sends an S-RTS packet to SU_d , including the availability information of the detected channel. Otherwise, SU_s sends the channel unavailability information to SU_d .
- 2) If an S-CTS packet from SU_d is not heard after a CTS timer, SU_s should perform a random backoff, as if it encounters a collision. If SU_s receives the information of channel availability from SU_d , SU_s and SU_d will start the transmission phase (please refer to Section III.C). If SU_s receives the information of channel unavailability from SU_d , SU_s will send C-RTS to the neighborhood of SU_c and SU_d .
- 3) If SU_s does not receive any feedback from SU_c , it then sends cooperation requirement again after a random backoff. If the feedback is successfully received, SU_s counts the number of SU_c according to the SU-selecting algorithm (please refer to Section IV). When the number of SU_c s satisfies the requirement of the cooperative sensing, SU_s stops sending cooperation requirement to the neighborhood of SU_c and divides the chosen SU_c s into a number of teams.

4) SU_s sends the cooperative information to the SU_c s and then join the cooperative sensing with SU_c s. Such information includes grouping information and the specific channels.

5) Upon receiving the sensing results, SU_s should declare the success of spectrum sensing and return to 1). Otherwise, SU_s should perform a random backoff, and return to 4).

Cooperative SU (SU_c)

1) Upon receiving the cooperation requirement, SU_c sends feedback to the source node SU_s and waits for the cooperative information.

2) If the information for the cooperation is not received after a CTS timer, SU_c assumes that the information is lost and then reverts to the original state. Otherwise, SU_c starts the channel sensing based on the cooperative information.

3) After the time duration t_s , SU_c determines the PU's activity on the detected channel and sends cooperation acknowledgement to SU_s with the sensing result.

Destination SU (SU_d)

1) SU_d senses the same channel with SU_s in a synchronous way. After the sensing time t_s , SU_d makes the final decision about the state (ON/OFF) of the channel, and waits for the sensing requirement from the source node SU_s .

2) If the destination node SU_d receives the sensing requirement with the sensing result from the source node SU_s , it delivers the sensing result back to SU_s . If the sensing result indicates that the channel is available, SU_d is ready for receiving data. Otherwise, SU_d waits for the cooperation requirement.

3) If cooperation requirement is received, SU_d will join the cooperative sensing and report the sensing results to SU_s . Then, SU_d returns to 2). If neither a sensing nor an cooperation requirement is heard after a timer, SU_d will go back to the initial state.

C. Transmission

After the source node SU_s and the destination node SU_d successfully find an available channel, they begin to use the channel to transmit data packets. Here, we use the T-RTS/T-CTS pair to indicate the transmission process. Before starting the transmission, SU_s will send T-RTS to SU_d for declaring the beginning of transmission. Upon receiving this requirement, SU_d replies T-CTS. If this feedback is received, SU_s sends the data packets to SU_d and sets acknowledgment timeout. When the acknowledgment from SU_d arrives, SU_s should declare the transmission success over the control channel. This success information ends the deferring of the neighboring SUs and starts a new round of reservation. If acknowledgment is not received after an acknowledgment timeout, SU_s should perform a random backoff and retransmit the data packets.

IV. REDUCING SENSING OVERHEAD VIA SU-SELECTING ALGORITHM

In this section, we would like to reduce the sensing overhead by introducing an SU-selecting algorithm. In this algorithm, we employ the alternative pattern and the channel data rate of the SUs' used channel as the cooperative SU's selection conditions.

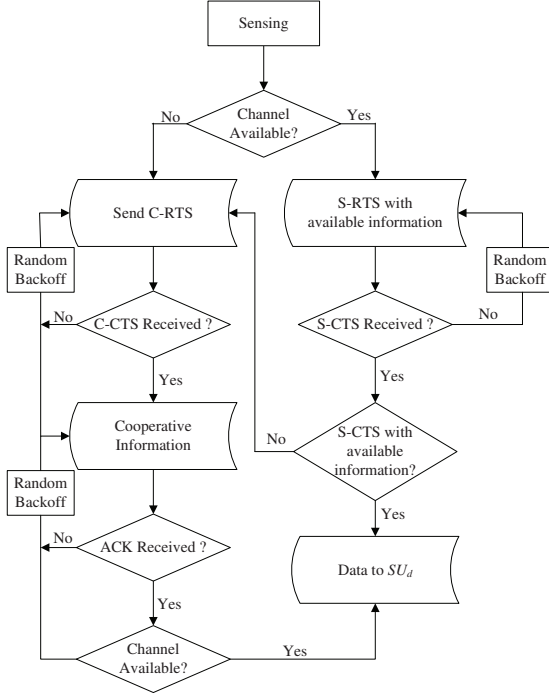


Fig. 1. The sensing work flow of SU_s .

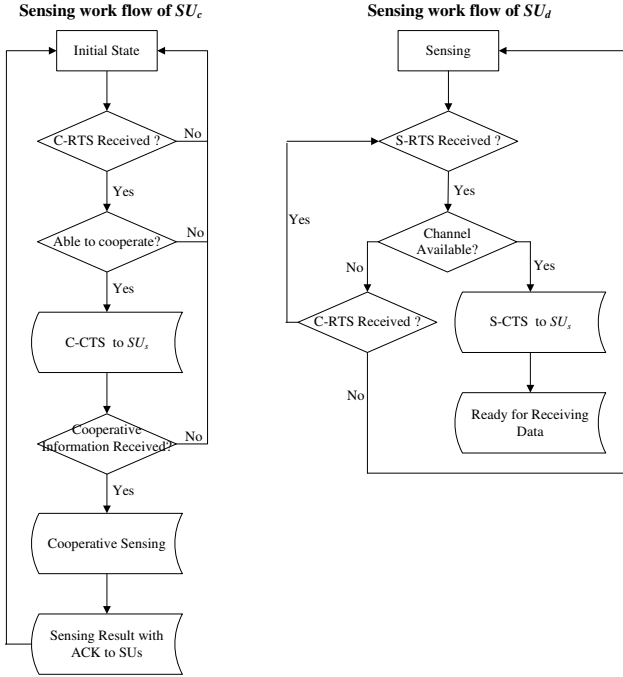


Fig. 2. The sensing work flow of SU_c and SU_d .

A. Channel Pattern for SUs

Each channel alternates between state ON and state OFF which is depending on the PUs' usage pattern. The channel that an SU uses may be busy after a period τ based on the previous idle status. During the busy period, the SUs are not allowed to access the channels which are occupied by a PU. In this case, if these SUs are selected for cooperative sensing,

the overhead of cooperation can be substantially reduced since sensing overhead is mainly incurred by ceasing transmissions during the cooperative sensing period. Let $I_\epsilon \in \{0, 1\}$ represents the binary channel state of channel ϵ . $I_\epsilon = 1$ refers to state ON and $I_\epsilon = 0$ refers to state OFF. Let $P_{I_\epsilon 1}(\tau)$ denotes the transition probability that the ϵ th channel will be busy after τ seconds with the initial state I_ϵ . We can express the transition probability $P_{01}(\tau)$ from channel state OFF to ON as [27]

$$P_{01}(\tau) = p - pe^{-(\mu_{OFF} + \mu_{ON})\tau} \quad (3)$$

where p is the channel availability.

It is shown that the $P_{01}(\tau)$ only relate with the most recent channel state $I_\epsilon = 0$ and τ , the time between the most recent sensing and the current sensing. Considering that τ is different among the channels, then $P_{01}(\tau)$ is accordingly different with distinct SUs. In order to reduce the sensing overhead, our goal is to select the cooperative SUs with the high $P_{01}(\tau)$. In the following section, we first present the optimal SUs-selecting algorithm in the time-invariant channel case. Then, we derive the optimal selecting algorithm for the case where the channel has time-varying feature.

B. SU-Selecting Algorithm

1) *Time-Invariant Channel Case:* A channel may stay at the idle state after τ seconds. The sensing overhead is expected to be high if the SUs who used these channels are chosen for cooperative sensing. Thereafter, in order to reduce sensing overhead, we select the cooperative SUs in the descending order of the probability $P_{01}(\tau)$. We can present the SU-selecting algorithm as follows.

- 1) SU_s delivers the Cooperative Sensing Request message (MSG-CSR) to the neighboring SU_{cs} when a PU's activity is detected on a channel.
- 2) The k th SU_c calculates $P_{01}(\tau_k)$ where τ_k represents the time duration from the moment of the most recent sensing to the moment of receiving MSG-CSR.
- 3) SU_s selects the cooperative SU_{cs} according to the descending order of $P_{01}(\tau_k)$.

The probability $P_{00}(\tau_k)$ can be alternatively employed since $P_{00}(\tau_k) = 1 - P_{01}(\tau_k)$. Hence, the SU-selecting algorithm can obtain the same strategy if we choose the cooperative SUs in the ascending order of the probability $P_{00}(\tau_k)$.

2) *Time-Varying Channel Case:* To reduce the sensing overhead, the SUs which have the highest $P_{01}(\tau)$ should be selected for cooperation in the time-invariant channel case. Here, the probability $P_{01}(\tau)$ represents the transition probability from state OFF to state ON. However, this strategy may not be efficient in the time-varying case where the channel data rate changes over the time. We choose the SUs not only based on the probability $P_{01}(\tau)$ but also based on the channel data rate of their used channels. The SUs' used channels which have both the lowest channel data rate and the highest $P_{01}(\tau)$ (or lowest $P_{00}(\tau)$) are selected to perform sensing and search the available channels. As a consequence, in the time-varying channel case, the SU-selecting algorithm can be provided as follows.

- 1) SU_s delivers the Cooperative Sensing Request message (MSG-CSR) to the SU_{cs} when PU's activity is detected on a channel.
- 2) The k th SU_c calculates $P_{00}(\tau_k)$, where τ_k represents the time duration from the moment of the most recent sensing to the moment of receiving the message MSG-CSR.
- 3) SU_s multiplies $P_{00}(\tau_k)$ by the channel data rate R_k of the k th SU's channel.
- 4) SU_s selects the cooperative SUs according to the ascending order of $P_{00}(\tau_k)R_k$.

V. ANALYSIS AND OPTIMIZATION FOR THE SATURATION NETWORKS

In this section, we will analyze the sensing overhead and throughput in a saturation networks. Our objective is to find two key design parameters: the number of cooperative teams and the number of SUs in one team. In a saturation network, we consider the CR network consisting of C licensed channels and K number of SUs. The set of licensed channels is denoted as $\mathbf{C} \equiv \{1, 2, \dots, C\}$ with $|\mathbf{C}| = C$. The set of SUs is denoted as $\mathbf{K} \equiv \{1, 2, \dots, K\}$ with $|\mathbf{K}| = K$. We allow the cooperative sensing scheme to choose a certain number of SUs which are further divided into U teams. Each team has q ($q \geq 1$) number of SUs and is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U and q satisfies $Uq \leq K$.

A. Time-Invariant Channel Case

1) *Sensing Overhead*: We define T_s as the total time duration spent by the k th cooperative SU after n_s number of the cooperative sensing. With the proposed group-based sensing strategy, up to U number of channels can be detected in one sensing period. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing and the variable n_s varies between 1 and $\lceil C/U \rceil$. If the channels can be found after n_s number of cooperative sensing, the cooperative SUs can not transmit any packets during $T_s = n_s t_s$ sensing periods. This operation is unfortunately unavoidable in the cooperative sensing. Let o_k^{TI} denotes the sensing overhead caused by the k th cooperative SU in the time-invariant situation. Then, we have

$$o_k^{TI} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (4)$$

where R_k denotes the channel data rate of the channel used by the k th cooperative SU. Since the channel data rate is a constant in the time-invariant channel case, we obtain sensing overhead as

$$o_k^{TI} = \int_0^{T_s} R P_{00}(\tau_k) d\tau_k. \quad (5)$$

2) *Throughput*: Let P_s represents the probability that a channel is successful found. This is equal to the probability that a channel is available and no false alarm is generated by q number of cooperative SUs. Then, we have $P_s = p[1 - P_f(q)]$, where p is the channel availability and $P_f(q)$ is given by (2). Let u denotes the number of available channels

that are found in a cooperative sensing. The probability distribution function of the random variable u is given by $\binom{U}{u}(1-P_s)^{U-u}P_s^u$. Then, we can obtain the probability, $P_{av,1}^{TI}$, that the available channels can be found in one cooperative sensing as

$$P_{av,1}^{TI} = \sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u. \quad (6)$$

With the proposed group-based sensing strategy, up to U number of channels can be detected in one sensing period. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. We can then obtain the probability P_{av,n_s}^{TI} that an available channel is found after n_s cooperative sensing.

$$P_{av,n_s}^{TI} = (1 - P_{av,1}^{TI})^{n_s-1} P_{av,1}^{TI}. \quad (7)$$

Let T_r denotes the average transmission time for an SU using discovered available channel. We can derive the throughput of an SU by using this channel as follows

$$\begin{aligned} \mathcal{T}^{TI} &= \sum_{n_s=1}^{\lceil C/U \rceil} P_{av,n_s}^{TI} T_r R \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} T_r R \left[1 - \sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u \right]^{n_s-1} \\ &\quad \times \left[\sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u \right] \end{aligned} \quad (8)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

To determine the optimal value of U and q , we introduce a new term *the achievable throughput*, which is defined as the difference between sensing overhead and throughput. It is clear that the achievable throughput is able to demonstrate the purely achieved throughput after removing the penalty with respect to sensing overhead. For this perspective, the concept is able to capture the inherent tradeoff in the cooperative sensing.

Suppose that the available channel is discovered at the n_s th detection by U number of teams. We can obtain the total sensing overhead \mathcal{O}^{TI} ,

$$\mathcal{O}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s P_{av,n_s}^{TI} q U o_k^{TI}. \quad (9)$$

Our objective is to find the optimal U and q for the group sensing in order to maximize the achievable throughput. The optimization problem is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{TI} = \mathcal{T}^{TI} - \mathcal{O}^{TI} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}, \end{aligned} \quad (10)$$

where $P_{f,th}$ and $P_{d,th}$ represent the threshold of the false alarm probability and detection probability, respectively. Based on the derived expression of \mathcal{T}^{TI} and \mathcal{O}^{TI} , the optimal number of cooperative teams and SUs in one team can be determined by solving (10). Considering the prohibitively high complexity of the optimization problem, we have resorted to numerical methods to find the optimal result to maximize the achievable throughput.

B. Time-Varying Channel Case

In this section, we will perform an analytical analysis on sensing overhead and throughput in the time-varying channel case. It is noteworthy that the analysis in the time-varying channel case is not a trivial extension of the analysis in the time-invariant channel case. On the one hand, the analysis in the time-invariant channel case is necessary to provide an easy understanding of the SUs cooperation behavior; and also the inherent trade-off between throughput and sensing overhead. On the other hand, the time-varying channel case is much more complicated than the time-invariant case by considering the complex channel dynamics. The development of sensing overhead and throughput is dependent on the channel dynamics, which leads to new equations for channel data rate, sensing overhead, throughput and hence achievable throughput in the time-varying case.

1) *Sensing Overhead*: Based on the SU-selecting algorithm, we can analyze the sensing overhead caused by the group-based sensing under the time-varying channel case. Let $\bar{R} = [R_1, R_2, \dots, R_M]$ represents the channel data rate vector of length M . Without loss of generality, we suppose $R_1 < R_2 < \dots < R_M$. Let $\bar{X} = [X_1, \dots, X_K]$ be a random sample from \bar{R} of length K . Hereby, the vector \bar{X} represents the specific value of a parallel sensing and hence has length K instead of M . Let $X_k (k \in \mathbf{K})$ denotes the k th order statistics of the sample. Employing order statistics theory [29], we can derive the probability $\Pr\{X_k = R_n\} (k \in \mathbf{K}; n \in \mathbf{M})$ which shows that the k th SU's channel data rate is equal to R_n . We suppose that there are $(h-1)$ number of samples in \bar{X} with the probability $\Pr\{X_i < R_n\} (1 \leq i \leq h-1; 1 \leq h \leq k)$; $(l-h+1)$ number of samples in \bar{X} with the probability $\Pr\{X_i = R_n\} (1 \leq i \leq l-h+1; k \leq l \leq K)$; and $(n-l)$ number of samples in \bar{X} with the probability $\Pr\{X_i > R_n\} (1 \leq i \leq n-l)$.

The random variables X_i are statistically independent and identically distributed with the generic form X , we have

$$\Pr\{X < R_n\} = \sum_{R_i < R_n} \Pr\{X = R_i\} = \sum_{i=1}^{n-1} \pi_i.$$

Since the $(h-1)$ samples could be any random samples from \bar{X} , we obtain the probability of this case $\binom{K-h+1}{h-1} (\sum_{i=1}^{n-1} \pi_i)^{h-1}$.

For the probability $\Pr\{X_i = R_n\}$, we have

$$\Pr\{X = R_n\} = \pi_n.$$

Since the number of $(l-h+1)$ samples could be any random samples from the rest of $(K-h+1)$ samples of X , we obtain the probability of this case as $\binom{K-h+1}{l-h+1} (\pi_n)^{l-h+1}$.

$$\begin{aligned} \Pr\{X_i > R_n\} &= 1 - \Pr\{X \leq R_n\} \\ &= 1 - \sum_{R_i < R_n} \Pr\{X = R_i\} \\ &= 1 - \sum_{i=1}^n \pi_i. \end{aligned}$$

Similarly, we obtain the probability of this condition as $\binom{K-l}{K-l} (1 - \sum_{i=1}^n \pi_i)^{K-l}$. By summarizing all possibilities, the probability $\Pr\{X_k = R_n\}$ is given by (13). Then, the channel

data rate of the selected SU, denoted as $R_k (k \in \mathbf{K})$, is given by

$$R_k = \sum_{n=1}^M \sum_{i=1}^n R_i \Pr\{X_k = R_n\}. \quad (11)$$

Let o_k^{TV} denotes the sensing overhead caused by the cooperative SU $_k$ after n_s number of cooperative sensing under the time-varying channel condition. We can obtain

$$o_k^{TV} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (12)$$

where $T_s = n_s t_s$ denotes the time spent by the k th cooperative SU after n_s number of sensing.

2) *Throughput*: Let v represents the number of spectrum channels that are found in a cooperative sensing. The probability density function (PDF) of the random variable v is given by $\binom{U}{v} (1 - P_s)^{U-v} P_s^v$ where P_s is given by (1). Let P_{av}^{TV} denotes the probability that an available channel can be found in one cooperative sensing in the time-varying channel case. Then, we have

$$P_{av}^{TV} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v. \quad (14)$$

We need to find the available channel with the highest channel data rate by the U teams. We will select the channel that has the highest channel data rate in these v channels for the SU to access. Let $R_m (1 \leq m \leq M)$ denotes the highest channel rate in these v number of channels. It is noteworthy that the subscript m in R_m represents the index of channel data rate, which ranges from 1 to M . Let $P_{rate,v}$ denotes the probability that there are channels whose maximum rate is no lower than $R_m (1 \leq m \leq M)$ in the founded v channels. Then, we have

$$P_{rate,v} = \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right]. \quad (15)$$

Conditioning on all possibilities on the random variable v , we obtain the probability P_{rate} that there are channels whose maximum rate is no lower than $R_m (1 \leq m \leq M)$

$$P_{rate} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v P_{rate,v}. \quad (16)$$

We obtain the probability $P_{maxrate}$ that R_m is the maximal channel data rate from all discovered available channels.

$$P_{maxrate} = (1 - P_{av}^{TV})^{n_s-1} P_{rate}. \quad (17)$$

With the proposed sensing strategy, each sensing period may find up to U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods.

$$\begin{aligned} \Pr\{X_k = R_n\} &= \sum_{l=k}^K \sum_{h=1}^k \left[\binom{K}{h-1} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} \binom{K-h+1}{l-h-1} (\pi_n)^{l-h+1} \binom{K-l}{K-l} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right] \\ &= \sum_{l=k}^K \sum_{h=1}^k \left[\frac{K!}{(h-1)!(l-h+1)!(K-1)!} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} (\pi_n)^{l-h+1} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right]. \end{aligned} \quad (13)$$

We can derive throughput of the SU by using this channel as

$$\begin{aligned} \mathcal{T}^{TV} &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{maxrate} T_r R_m \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M T_r R_m (1 - P_{av}^{TV})^{n_s-1} \\ &\quad \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right] \end{aligned} \quad (18)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

We formulate the achievable throughput optimization problem by considering both throughput and sensing overhead in the time-varying channel condition. The total sensing overhead \mathcal{O}^{TV} is given by

$$\mathcal{O}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s q U P_{av}^{TV} o_k^{TV}. \quad (19)$$

Consequently, the achievable throughput maximization problem in the time-varying channel case is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{TV} = \mathcal{T}^{TV} - \mathcal{O}^{TV} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}, \end{aligned} \quad (20)$$

where \mathcal{T}^{TV} and \mathcal{O}^{TV} are given by (18) and (19), respectively. By solving (20), we can find the optimal U and q for the group sensing in order to maximize the achievable throughput.

VI. ANALYSIS AND OPTIMIZATION FOR THE NON-SATURATION NETWORKS

In this section, we will derive the sensing overhead and throughput in the non-saturation networks. Suppose that an SU may have an empty queue. In this network, we consider a discrete-time queue with an infinite capacity buffer for the queuing behavior of an SU. The packets arrival of the SUs is assumed to be a Poisson process with arrival rate λ_{pac} . The packets are served on a First-In First-Out (FIFO) basis. The service time of each packet is modeled as identically distributed nonnegative random variables, denoted as $\chi_n (n \geq 1)$, whose arrival process is independent to each another. The similar assumption has been frequently used in the literature, e.g [13], [28]. Let $F(t)$ denotes the service time Cumulative Distribution Function (CDF) with mean $0 < 1/\mu = \int_0^\infty t dF(t)$. Let ρ represents the traffic

load and it is given by $\rho = \frac{\lambda_{pac}}{\mu}$. For a practical system, the traffic load is less than 1, i.e. $\rho < 1$.

Similar to saturation network, we still consider the CR network consisting of C licensed channels and K number of SUs. The cooperative SUs are divided into U teams. Each team has q ($q \geq 1$) number of SUs. Each team is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U and q also satisfies $Uq \leq K$. Next, we will formulate the throughput maximization problem with time-invariant and time-varying channel, respectively.

A. Time-Invariant Channel Case

Since the channel data rate will not change with the time in time-invariant channel case. The packet service time is a constant, which means we are able to employ the single-server queuing model, $M/D/1$, to evaluate the group sensing scheme with time-invariant channel.

Based on the result of [29], the variance of service time $E(\chi^2) = 0$ in the $M/D/1$ model. Let \bar{N}_q^{TI} denotes the average number of packets in a queue for time-invariant channel case. Then, we have

$$\bar{N}_q^{TI} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\rho^2}{2(1-\rho)}. \quad (21)$$

1) *Sensing Overhead*: To reduce the sensing overhead, we still select qU SUs that have the lowest channel data rate and least $P_{00}(t)$ among K SUs in the non-saturation network. As explained, each group sensing can sense U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of group sensing. Let N_{sense}^{TI, n_s} be the total number of packets that can be transmitted in the n_s number of group sensing by the qU sensing SUs if they are not participating the group-based cooperative sensing. N_{sense}^{TI, n_s} is given by

$$N_{sense}^{TI, n_s} = \min \left\{ n_s q U \bar{N}_q^{TI}, (q U T_s R_{use})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (22)$$

where R_{use} denotes the channel data rate of the using channel, l denotes the length of a packet, $T_s = t_s n_s$ and \bar{N}_q^{TI} is given by (21).

Suppose that the available channel is discovered at the n_s th detection by U number of teams in non-saturation network. Then, in a time-invariant channel case, we can obtain the total sensing overhead $\mathcal{O}_{nonsat}^{TI}$,

$$\mathcal{O}_{nonsat}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av, n_s}^{TI} N_{sense}^{TI, n_s} l \quad (23)$$

where P_{av,n_s}^{TI} is given by (7).

2) *Throughput*: Let T_r denotes the average transmission time for an SU using discovered available channel. In the time-invariant channel case, the average number of packets that SUs send during T_r at the equilibrium state is given by

$$N_D^{TI} = \min \left\{ \bar{N}_q^{TI}, (T_r R_{use})/l \right\} \quad (24)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

With the proposed sensing strategy, each sensing period may find up to U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. Hence, we can derive the throughput of an SU by using the discovered available channel as follows.

$$\mathcal{T}_{nonsat}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av,n_s}^{TI} N_D^{TI} l \quad (25)$$

where the item P_{av,n_s}^{TI} is given by (14).

In terms of the achievable throughput maximization, we formulate the following problem

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{nonsat}^{TI} = \mathcal{T}_{nonsat}^{TI} - \mathcal{O}_{nonsat}^{TI} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}. \end{aligned} \quad (26)$$

B. Time-Varying Channel Case

Considering the time-varying channel case, the channel data rate may vary from time slot to time slot. This alternative indicates that an SU's capacity is a random variable. Following this reasoning, we can use the M/G/1 queuing model.

1) *Sensing Overhead*: Since the service time of each packets depends on the channel data rate, we can express the CDF $F(t)$ as

$$F(t) = l/R_i(t) \quad (27)$$

where $R_i(t)$ denotes the channel data rate of the i th channel state at the t th time slot. Let \bar{N}_q^{TV} denotes the average number of packets in a queue for time-varying channel case. Then, we have

$$\bar{N}_q^{TV} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\lambda^2 E(\chi^2) + \rho^2}{2(1-\rho)} \quad (28)$$

where $E(\chi^2) = \int_0^\infty t^2 dF(t)$.

In the time-varying channel case, let N_{sense}^{TV,n_s} be the total number of packets that can not be transmitted by the qU cooperative SUs in n_s number of group sensing. N_{sense}^{TV,n_s} is given by

$$N_{sense}^{TV,n_s} = \min \left\{ n_s q U \bar{N}_q^{TV}, (q U T_s R_{use})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (29)$$

where $T_s = t_s n_s$ and \bar{N}_q^{TV} is given by (28).

Then, in a time-varying channel case, the total sensing overhead for discovering an available channel can be obtained as follows

$$\mathcal{O}_{nonsat}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av}^{TV} N_{sense}^{TV,n_s} l. \quad (30)$$

2) *Throughput*: We use T_r to denote the average transmission time for an SU using discovered available channel in the time-varying channel case. Then, the average number of packets that SUs send during T_r is given by

$$N_D^{TV} = \min \left\{ \bar{N}_q^{TV}, (T_r R_{use})/l \right\} \quad (31)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

The proposed sensing strategy may find up to U number of channels during each sensing period. All channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. Suppose that the available channel can be found after n_s number of group sensing, we can obtain the throughput of an SU by using discovered available channel in the time-varying channel case.

$$\mathcal{T}_{nonsat}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{maxrate} N_D^{TV} l \quad (32)$$

where the item $P_{maxrate}$ is given by (17).

Finally, we formulate the following problem in terms of achievable throughput maximization

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{nonsat}^{TV} = \mathcal{T}_{nonsat}^{TV} - \mathcal{O}_{nonsat}^{TV} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}. \end{aligned} \quad (33)$$

Considering the complexity of the optimization problems, we still use numerical methods to find the optimal result to maximize the achievable throughput in non-saturation network. The optimal results are provided in the following section under time-invariant and time-varying channel condition, respectively.

VII. SIMULATION RESULTS

In this section, we demonstrate the performance of the proposed GC-MAC in CR networks. The network consists of total $C = 10$ licensed channels. The channel parameter of the OFF period $\mu_{OFF} = 1/100$. We concentrate on the low SNR situation, the SNR threshold for a PU at the tagged SU is $\gamma = -10dB$. The channel bandwidth is 1 MHz and the target probability of detection $P_d = 0.9$ which is a important parameter used by 802.22 standard [30]. The length of RTS/CTS packets and sensing period are 40Bytes and 1ms, respectively. Considering the time-varying channel case, the number of channel data rate state is $M = 10$. Accordingly, the channel data rate of each channel ranges between $0.1MB/s - 1MB/s$, which decreases or increases its value by 10(%) once every 5ms.

Table.I shows the impacts of the number of cooperative teams and the number of SUs in one team on the achievable saturation throughput in the time-invariant channel situation. In these examples, the channel availability p is set as 1/2. We can determine the optimal achievable throughput by choosing appropriate parameters. From Table.I, we observe that the achievable throughput is maximized as 0.9822. In the time-varying channel case, Table.II shows the achievable saturation throughput that the maximal value is 0.8154. The saturation

TABLE I
THE ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATION OF U AND j IN TIME-INVARIANT CHANNEL CASE.

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.9422	0.9365	0.9428	0.9359	0.9162	0.9208	0.9184	0.9126	0.9050	0.8746
$q=2$	0.9631	0.9822	0.9376	0.9061	0.8635	—	—	—	—	—
$q=3$	0.9616	0.9151	0.8797	—	—	—	—	—	—	—
$q=4$	0.9366	0.8708	—	—	—	—	—	—	—	—
$q=5$	0.9059	0.8454	—	—	—	—	—	—	—	—
$q=6$	0.8887	—	—	—	—	—	—	—	—	—
$q=7$	0.8712	—	—	—	—	—	—	—	—	—
$q=8$	0.8527	—	—	—	—	—	—	—	—	—
$q=9$	0.8347	—	—	—	—	—	—	—	—	—
$q=10$	0.8163	—	—	—	—	—	—	—	—	—

TABLE II
THE ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATION OF U AND j IN TIME-VARYING CHANNEL CASE.

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.7839	0.7798	0.7764	0.7713	0.7645	0.7600	0.7544	0.7483	0.7421	0.7341
$q=2$	0.7907	0.8154	0.7282	0.7935	0.7245	—	—	—	—	—
$q=3$	0.7864	0.7730	0.7515	—	—	—	—	—	—	—
$q=4$	0.7804	0.7571	—	—	—	—	—	—	—	—
$q=5$	0.7731	0.7474	—	—	—	—	—	—	—	—
$q=6$	0.7681	—	—	—	—	—	—	—	—	—
$q=7$	0.7630	—	—	—	—	—	—	—	—	—
$q=8$	0.7681	—	—	—	—	—	—	—	—	—
$q=9$	0.7525	—	—	—	—	—	—	—	—	—
$q=10$	0.7472	—	—	—	—	—	—	—	—	—

throughput in the time-varying case is lower than that in the time-invariant case. This is expected since the channel data rate may be reduced in the time-varying condition due to fading and signal variation. Similarly, we can obtain the maximal non-saturation throughput in the time-invariant channel case and the time-invariant channel case as 0.9107 and 0.8095, respectively.

A. Achievable Throughput

We compare our GC-MAC which uses group-based cooperative sensing scheme (GCSS) with accuracy priority cooperative sensing scheme (ACSS) [11] and efficiency priority cooperative sensing scheme (ECSS) [13]. In the scheme ACSS, every cooperative SU monitors a single channel during each sensing period. The main focus of this scheme is to improve sensing accuracy of a PU's activity. In the scheme SCSS, the cooperative SUs are assigned to sense different channels simultaneously for the sensing efficiency enhancement. This sensing operation assumes that the sensing of each channel by a single SU is accurate, which however may be difficult to achieve in practical CR networks.

1) *Time-Invariant Channel Case*: Fig. 3 shows the throughput comparison among GCSS, ACSS and ECSS in the time-invariant channel case when $p = 2/3$ and $1/2$. In this example, the sensing accuracy requirement is set as $P_{f,th} = 0.05$. It is observed that the achievable throughput in all three schemes increases with higher channel availability p , which is intuitively understandable. The result indicates that GCSS is able to achieve much higher throughput than ACSS and ECSS. This is because GCSS is able to search and find more spectrum opportunities. When the number of the cooperative SUs becomes larger, there is higher chance to find the available channels which leads to less sensing overhead. In addition,

ECSS uses all SUs to sense different channels, which causes a less sensing accuracy of single channel and leads to lower throughput. Comparatively, the proposed GCSS chooses the optimal number of teams and the number of SUs in each team. In this case, sensing overhead is significantly reduced and throughput increases. As a consequence, our proposed GCSS is able to achieve high sensing efficiency with low sensing overhead.

Fig.4 shows the non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-invariant channel case when $p = 2/3, 1/2$. Again, the $P_{f,th} = 0.05$ is assumed as 0.05. It can be observed that, GCSS substantially outperforms the other two schemes. In addition, we notice that it will obtain higher throughput if the channel availability p becomes larger.

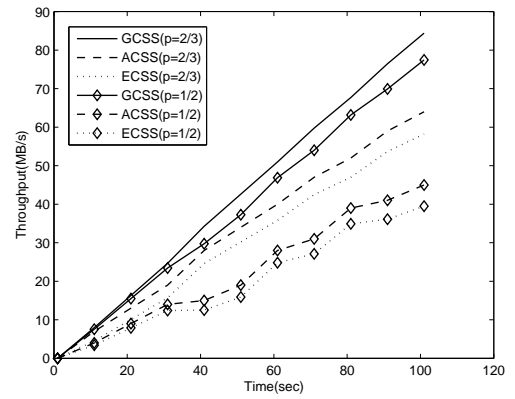


Fig. 3. The saturation throughput in the time-invariant channel case with different p .

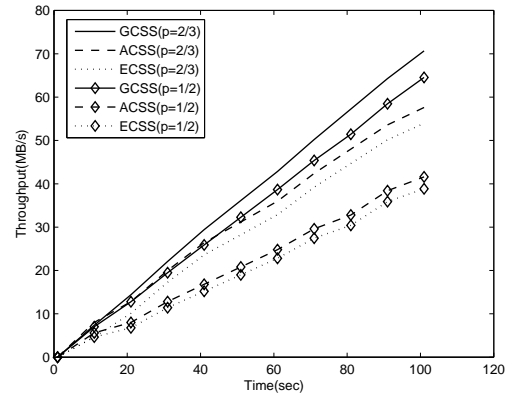


Fig. 4. The non-saturation throughput in the time-invariant channel case with different p .

2) *Time-Varying Channel Case*: Fig.5 and Fig.6 show the saturation and non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-varying channel case when $p = 2/3, 1/2$ and $P_{f,th} = 0.05$. The comparison indicates that GCSS is able to achieve higher throughput than ACSS and ECSS. This is because GCSS is able to detect and find more spectrum opportunities even when the channel

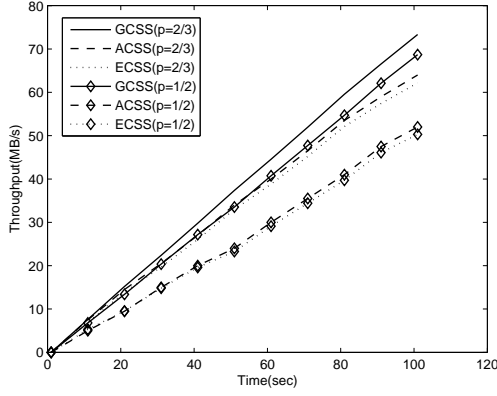


Fig. 5. The saturation throughput in the time-varying channel case with different p .

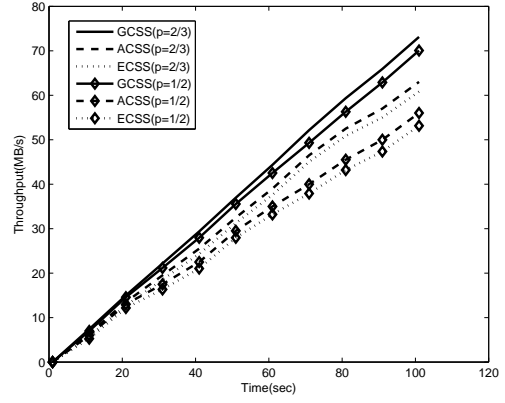


Fig. 7. The saturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

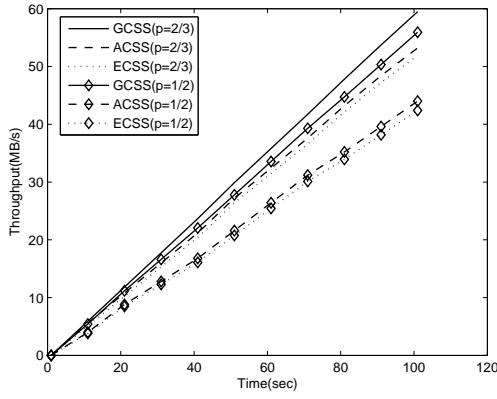


Fig. 6. The non-saturation throughput in the time-varying channel case with different p .

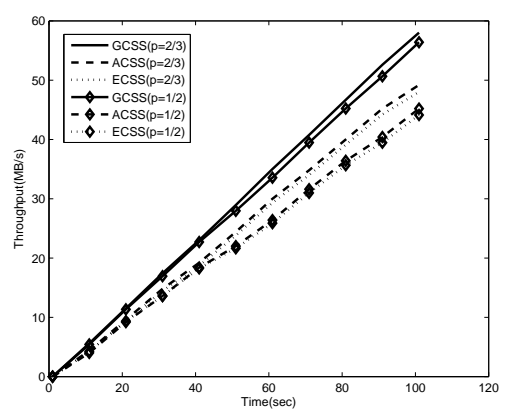


Fig. 8. The non-saturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

is dynamic. When the number of cooperative SUs becomes larger, our scheme not only finds the available channel quicker but also chooses the channel with maximal rate if more than one available channels are found. Moreover, with the comparison to ECSS, GCSS has the advantage of reducing sensing overhead. As a consequence, the proposed GCSS achieves higher throughput in the time-varying channel case.

In addition, we illustrate the achievable throughput comparison among GCSS, ACSS and ECSS under the complex-valued signal model. Fig.7 and Fig.8 show the saturation and non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-varying channel case, respectively. We observe that GCSS also can obtain higher throughput than that in ACSS and ECSS. This observation indicates the effectiveness of our proposed MAC protocol in both of the real-valued and complex-valued signal model.

B. Sensing Overhead

1) *Time-Invariant Channel Case*: Fig.9 shows sensing overhead among GCSS, ACSS and ECSS in the time-invariant channel case for saturation situation. It is observed that GCSS generates the lowest sensing overhead. This can be explained as follows. GCSS selects the SUs to cooperate

by using the SU-selecting algorithm. The algorithm chooses the SUs with low channel available probability (P_{00}) for the cooperative sensing. This operation can substantially reduce sensing overhead by avoiding the temporary stopping of the ongoing transmissions when their channels are occupied by PUs. Comparatively, ACSS and ECSS have no similar mechanisms and hence generate higher sensing overhead. Fig.10 shows the sensing overhead for non-saturation situation. Similar observations and conclusions can be made. In addition, we notice that sensing overhead decreases when the channel availability p becomes larger. With more channel availability, there are more chances to find spectrum opportunities in a fixed period; and hence less sensing overheads.

2) *Time-Varying Channel Case*: Considering the time-varying channel case, Fig.11 and Fig.12 show the sensing overhead with different channel availability p under saturation and non-saturation situation, respectively. It is clear that sensing overhead becomes lower when the channel availability p increases. Again, the proposed GCSS incurs lower sensing overhead than ACSS and ECSS. With the time-varying channel, we have considered the channel dynamics and rate variation in selecting appropriate SUs to perform sensing. Following this way, sensing overhead in traditional cooperative

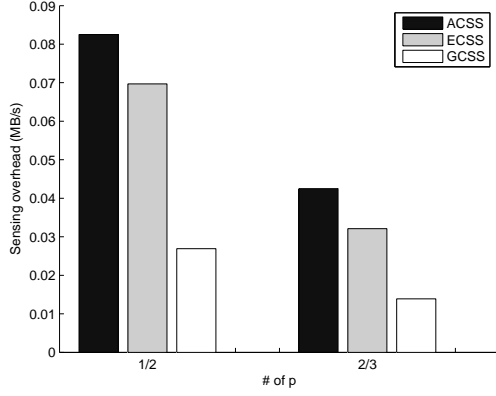


Fig. 9. The sensing overhead in the time-invariant channel case with different p for saturation situation.

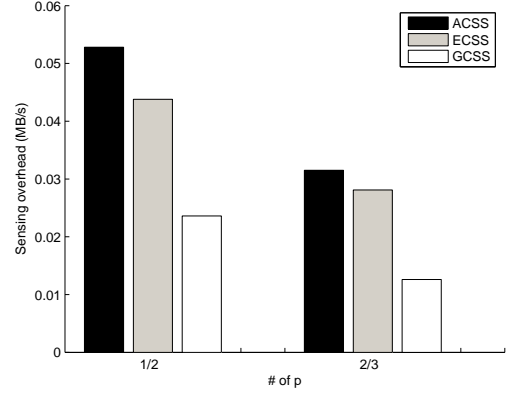


Fig. 12. The sensing overhead in the time-varying channel case with different p for non-saturation situation.

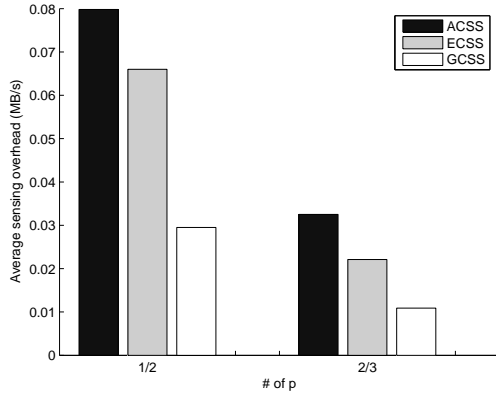


Fig. 10. The sensing overhead in the time-invariant channel case with different p for non-saturation situation.

sensing can be partially avoided.

VIII. CONCLUSION

We design an efficient MAC protocol with selective grouping and cooperative sensing in cognitive radio networks. In our

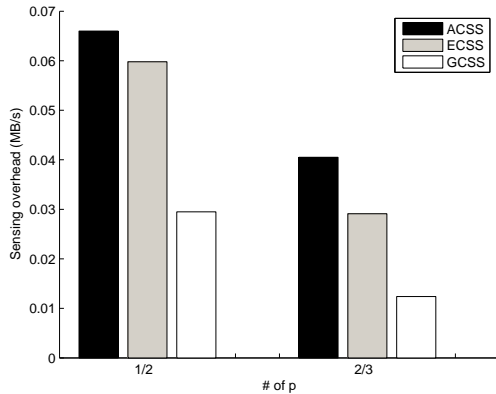


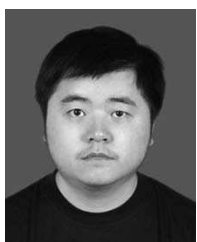
Fig. 11. The sensing overhead in the time-varying channel case with different p for saturation situation.

protocol, the cooperative MAC can quickly discover the spectrum opportunities without degrading sensing accuracy. An SU-selecting algorithm is proposed for specifically choosing the cooperative SUs in order to substantially reduce sensing overhead in both time-invariant and time-varying channel cases. We formulate the throughput maximization problems to determine the crucial design parameters and to investigate the trade-off between sensing overhead and throughput. Simulation results show that our proposed protocol can significantly reduced sensing overhead without degrading sensing accuracy.

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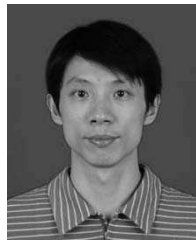
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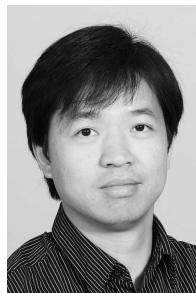


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An Efficient MAC Protocol with Selective Grouping and Cooperative Sensing in Cognitive Radio Networks

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Abstract—In cognitive radio networks, spectrum sensing is a crucial technique to discover spectrum opportunities for the Secondary Users (SUs). The quality of spectrum sensing is evaluated by both sensing accuracy and sensing efficiency. Here, sensing accuracy is represented by the false alarm probability and the detection probability while sensing efficiency is represented by the sensing overhead and network throughput. In this paper, we propose a group-based cooperative Medium Access Control (MAC) protocol called GC-MAC, which addresses the tradeoff between sensing accuracy and efficiency. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel while SUs in the same team perform the joint detection on the targeted channel. The sensing process will not stop unless an available channel is discovered. To reduce the sensing overhead, an SU-selecting algorithm is presented to selectively choose the cooperative SUs based on the channel dynamics and usage patterns. Then, an analytical model is built to study the sensing accuracy-efficiency tradeoff under two types of channel conditions: time-invariant channel and time-varying channel. An optimization problem that maximizes achievable throughput is formulated to optimize the important design parameters. Both saturation and non-saturation situations are investigated with respect to throughput and sensing overhead. Simulation results indicate that the proposed protocol is able to significantly decrease sensing overhead and increase network throughput with guaranteed sensing accuracy.

Index Terms—Cognitive MAC, spectrum sensing, sensing accuracy, sensing efficiency.

I. INTRODUCTION

Recently, the explosive increase of wireless devices and applications poses a serious problem of compelling need of numerous radio spectrum. The problem is greatly caused by the current fixed frequency allocation policy, which allocates a fixed frequency band to a specific wireless system. On the contrary, a recent report published by the Federal Communication Commission (FCC) reveals that most of the licensed spectrum is rarely utilized continuously across time and space [1] [2]. In order to address the spectrum scarcity and

the spectrum under-utilization, Cognitive Radio (CR) has been proposed to effectively utilize the spectrum [3] [4]. In the CR networks, the Secondary (unlicensed) Users (SUs) are allowed to opportunistically operate in the frequency bands originally allocated to the Primary (licensed) Users (PUs) when the bands are not occupied by PUs. SUs are capable to sense unused bands and adjust transmission parameters accordingly, which makes CR an excellent candidate technology for improving spectrum utilization.

Spectrum sensing is a fundamental technology for SUs to efficiently and accurately detect PUs in order to avoid the interference to primary networks. However, in CR networks, many unreliable conditions [5]–[7], such as channel uncertainty, noise uncertainty and no knowledge of primary signals, will degrade the performance of spectrum sensing. Cooperative sensing [8]–[16], has been studied extensively as a promising alternative to improve sensing performance at both of the physical (PHY) level and the medium access control (MAC) level. The main interest of this paper is the cooperative sensing mechanism at the MAC level, which performs sensing operations in two aspects: 1) assign multiple SUs to sense a single channel for improving the sensing accuracy; 2) assign cooperative SUs to search for available spectrums in parallel to enhance sensing efficiency.

The improvement of sensing accuracy is extensively treated in [11]–[13]. The study in [11] reports a cooperative sensing approach through multi-user cooperation and evaluates the sensing accuracy. The authors of [12] consider cooperative sensing by using a counting rule and derive optimal strategies under both the Neyman-Pearson criterion and the Bayesian criterion. The study in [13] presents a new cooperative wide-band spectrum sensing scheme that exploits the spatial diversity among multiple SUs which also contributes to improve the sensing accuracy. These studies have mainly focused on improving sensing accuracy while sensing efficiency has been ignored. The enhancement for sensing efficiency has been investigated in [14][15]. The study in [14] introduces an opportunistic multi-channel MAC protocol which integrate two novel cooperative sensing mechanisms, i.e., random sensing policy and negotiation-based sensing policy. The latter strategy assigns SUs to collaboratively sense different channels to improve the sensing efficiency. For the sake of reducing sensing overhead, the authors of [15] propose a multi-channel cooperative sensing scheme, where the cooperative SUs are optimally selected to sense the distinct channels at the same time for sensing efficiency. These works assume that the

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sensing accuracy of one channel by a single SU is completely true which is may not be practical in real communication systems.

In addition, literatures above did not consider the design of the cooperative MAC protocol for distributed networks and perform theoretical analysis of sensing overhead and throughput. Hence, we are interested in achieving both sensing accuracy and sensing efficiency by introducing a cooperation protocol in MAC layer for CR networks. Several cognitive MAC protocols have been proposed in the literature to address various issues in CR network [14][18][21]-[26]. However, these protocols do not leverage the benefit of cooperation at MAC layer for enhancing the sensing efficiency without degrading the sensing accuracy.

In this paper, we propose a group-based cooperative MAC protocol called GC-MAC. In GC-MAC, the cooperative SUs are grouped into several teams. During a sensing period, each team senses a different channel. The sensing process will not stop unless an available spectrum channel is discovered. The purpose of team division has twofold: 1) sensing a channel by several SUs for the improvement of sensing accuracy; 2) finding more spectrum opportunities by sensing distinct channels by different teams. As a consequence, multiple distinct channels can be simultaneously detected within one sensing period which leads to the enhancement of sensing efficiency.

To reduce the sensing overhead, we propose an SU-selecting algorithm for GC-MAC protocol. In the SU-selecting algorithm, we selectively choose the optimal number of the cooperative SUs for each team based on the channel occupation dynamics in order to substantially reduce sensing overhead. We analyze the sensing overhead and throughput in the saturation and no-saturation network cases, respectively. In the saturation networks, each SU always has data to transmit. In the non-saturation networks, an SU may have an empty queue. In every network case, we consider two types of channel conditions: time-invariant channel and time-varying channel. In each condition, the sensing overhead and the throughput are incorporated into an achievable throughput maximization problem, which is formulated to find the key design parameters: the number of the cooperative teams and the number of SUs in one team. Furthermore, we present extensive examples to demonstrate the sensing efficiency comparing with the existing schemes and to show the determination of the crucial parameters. Simulation results demonstrate that our proposed scheme is able to achieve substantially higher throughput and lower sensing overhead, comparing to existing mechanisms.

The remainder of this paper is organized as follows. In Section II, the system models are introduced. Section III reports our proposed group-based MAC protocols for cooperative CR network. Section IV introduces an SU-selecting algorithm for appropriately selecting the cooperative SUs so as to reduce the sensing overhead. Then, we study the sensing overhead and achievable throughput in the saturation and non-saturation networks in Section V and Section VI, respectively. Section VII evaluates the performance of the proposed GC-MAC protocol based on our developed analytical models. Finally, we draw our conclusions in Section VIII.

II. SYSTEMS MODELS

A. Channel Usage Model

We assume that each licensed channel alternates between ON and OFF state, of which the OFF time is not used by PUs and hence can be exploited by the SUs. Assume that the durations of the ON and the OFF period are independently exponentially distributed. For a given licensed channel, the duration of ON period follows an exponentially distributed with parameter μ_{ON} and the duration of OFF period with an exponentially distributed parameter μ_{OFF} . We define the channel availability as the normalized period which is available for SUs. Let p denotes the channel availability. Then, we have $p = \frac{\mu_{ON}}{\mu_{OFF} + \mu_{ON}}$. Similar to [14], in this paper, we mainly consider that the licensed channels used by the same set of PUs, i.e., the licensed channel availability information sensed by each SUs is consistent among all SUs.

We consider two scenarios depending on the channel dynamics. The first is the time-invariant channel with unchanged channel data rate R . The throughput of the SU by using time-invariant channel only depends on the constant data rate and the valid transmission time T_T . The second type of channel is the Time-Varying Channel. The Finite-State Markov Channel (FSMC) model is employed to model the dynamics of the time-varying channel [20]. The dynamics of the time-varying channel is partitioned based on the channel data rate. It is reasonable to employ the channel data rate instead of Signal-to-Noise Ratio (SNR) which has been used in conventional FSMC model. Since the channel data rate is closely relevant to the application layer requirements and hence its usage facilitates the construction of resource demands from an application perspective. The set of the channel state is denoted as $\mathbf{M} \equiv \{1, 2, \dots, M\}$ with $|\mathbf{M}| = M$. Let c_i represents the channel state i ($i \in \mathbf{M}$). The state space is denoted as $\mathbf{S} \equiv \{c_i, i \in \mathbf{M}\}$. Let π_i ($i \in \mathbf{M}$) represents the steady-state probability at state c_i . Then, the steady-state probability can be solved using the similar technique in [20]. During data transmission within a frame, the time-variation is slow enough that the channel data rate does not change substantially. This assumption is acceptable due to the short data transmission period within a frame and has been frequently used, e.g. [19] [27].

B. Energy Detection Model

In order to discuss our problem, we employ Energy Detection [6] as the spectrum sensing scheme. Both of the real-valued signal model and the complex-valued signal model are used to describe the received signal at the SU's receiver.

1) *Real-Valued Signal Model:* Let t_s be the sensing time and f_s be the sample frequency during sensing time. We denotes N as the number of samples in a sensing period, i.e. $N = t_s f_s$. The received signal $r_k(n)$ at the n th sample and the k th SU is given by,

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ s_k(n) + w_k(n), & H_1 \end{cases}$$

where H_0 represents the hypothesis that PUs are absent, and H_1 represents the hypothesis that PUs are present. $s_k(n)$

represents the PU's transmitted signal which is assumed as a real-valued Gaussian signal with mean zero and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with mean zero and variance σ_w^2 .

Let $e_k(r)$ denotes the test statistic of the k th SU. Then, we have $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false alarm probability of k th SU are given by,

$$P_d^k = Pr[e_k(r) > \lambda | H_1], \quad P_f^k = Pr[e_k(r) > \lambda | H_0]$$

where λ is a decision threshold of energy detector for a SU.

The test statistic $e(r)$ is known as Chi-square distribution with $\frac{e(r)}{\sigma_w^2} \sim \chi_N^2$ under hypothesis H_0 , and $\frac{e(r)}{\sigma_s^2 + \sigma_w^2} \sim \chi_N^2$ under hypothesis H_1 . However, if the number of samples is large, we can use the Central Limit Theorem (CLT) to approximate the Chi-square distribution by Gaussian distribution [6] under hypothesis $H_z (z = 0, 1)$ with mean μ_z and variance σ_z^2 as,

$$\begin{cases} \mu_0 = N\sigma_w^2, & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(\sigma_s^2 + \sigma_w^2), & \sigma_1^2 = 2N(\sigma_s^2 + \sigma_w^2)^2, & H_1. \end{cases}$$

Therefore, the probabilities P_d^k and P_f^k can be approximated in terms of the Q function is given by,

$$P_d^k = Q\left(\frac{\lambda - N(\sigma_s^2 + \sigma_w^2)}{\sqrt{2N(\sigma_s^2 + \sigma_w^2)}}\right), \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^2}}\right)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$.

2) *Complex-Valued Signal Model*: Considering the complex-valued signal model, the received signal $r_k(n)$ at the n th sample and the k th SU can be given by,

$$r_k(n) = \begin{cases} w_k(n), & H_0 \\ h_k s_k(n) + w_k(n), & H_1 \end{cases}$$

where the channel coefficients h_k is zero-mean, unit-variance complex Gaussian random variables. $s_k(n)$ represents the PU's transmitted signal which is assumed as a Gaussian signal with mean zero and variance σ_s^2 . $w_k(n)$ denotes a Gaussian process with mean zero and variance σ_w^2 .

The test statistic of the k th SU $e_k(r) = \sum_{n=1}^N |r_k(n)|^2$. The detection and false alarm probability of k th SU are given by,

$$P_d^k = Pr[e_k(r) > \lambda_c | H_1], \quad P_f^k = Pr[e_k(r) > \lambda_c | H_0],$$

where λ_c is a decision threshold of energy detector for a single SU considering the complex-valued signal model. For a large N , the distribution of $e_k(r)$ can be approximated as Gaussian distribution [6] with mean μ_z and variance σ_z^2 under hypothesis $H_z (z = 0, 1)$ as,

$$\begin{cases} \mu_0 = N\sigma_w^2, & \sigma_0^2 = 2N\sigma_w^4, & H_0 \\ \mu_1 = N(|h_k|^2 \sigma_s^2 + \sigma_w^2), & \sigma_1^2 = 2N(|h_k|^2 \sigma_s^2 + \sigma_w^2)^2, & H_1 \end{cases}$$

Finally, we can obtain the probabilities P_d^k and P_f^k in terms of the Q function as

$$P_d^k = Q\left(\frac{\lambda - N(|h_k|^2 \sigma_s^2 + \sigma_w^2)}{\sqrt{2N(|h_k|^2 \sigma_s^2 + \sigma_w^2)}}\right), \quad P_f^k = Q\left(\frac{\lambda - N\sigma_w^2}{\sqrt{2N\sigma_w^2}}\right),$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}} dt$.

C. Counting Rule

In order to improve sensing performance, an efficient fusion rule is needed to make final decision to the availability of the channel. Depending on every SUs' individual decision from one team, there are three popular fusion rules: And-rule, OR-rule and Majority-rule [19]. And-rule mainly focuses on maximizing the discovery of spectrum opportunities which are deemed to be exist if only one decision says there is no PU. In OR-rule, as far as limit the interference to the PU, the spectrum is assumed to be available only when all the reporting decisions declare that no PU is present. The last Majority-rule is based on majority of the individual decisions. If more than half of the decisions declare the appearance of primary user, then the final decision claims that there is a primary user. Without loss of generality, we use the Majority-rule in this paper with the assumption that all the individual decisions are independent, and supposing that $P_d^k = P_d$ and $P_f^k = P_f$ [19]. Then the joint detection probability and false alarm probability by j number of SUs are given by

$$P_d(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_d)^{j-\lceil \frac{j}{2} \rceil - y} P_d^{\lceil \frac{j}{2} \rceil + y}, \quad (1)$$

$$P_f(j) = \sum_{y=0}^{j-\lceil \frac{j}{2} \rceil} \binom{j}{\lceil \frac{j}{2} \rceil + y} (1 - P_f)^{j-\lceil \frac{j}{2} \rceil - y} P_f^{\lceil \frac{j}{2} \rceil + y}. \quad (2)$$

III. GC-MAC: GROUP-BASED COOPERATIVE MAC PROTOCOL

In this section, we present the specifications of the proposed MAC protocol, together with the group-based cooperative spectrum sensing scheme and the SU-selecting algorithm. To describe our protocol conveniently, we have the following assumptions:

- Each SU is equipped with a single antenna which can not operate the sensing and transmission at the same time. According to this constraint, the sensing overhead caused by sensing is unavoidable and cannot be neglected in protocol design.
- A common control channel is available for all SUs to communicate at any time.
- An SUs can be assigned to perform cooperative sensing even when they have the packets to transmit.

A time frame of the secondary network operation is divided to three phases: reservation, sensing and transmission. All SUs are categorized into three types:

- Source SU (SU_s): an SU that has data to transmit.
- Cooperative SUs (SU_c): SUs that are selected for cooperative sensing.
- Destination SU (SU_d): an SU that receives the data packet from the source SU.

A. Reservation

In GC-MAC, any SU_s entering the network first try to perform a handshake with SU_d on the control channel to

reserve a data channel. This allows the SU_s and SU_d to switch to the chosen channel for data transmission. Here, we use R-RTS/R-CTS packets for SU_s and SU_d to compete the data channel with other SUs. The SU_s will listen to control channel for a time interval T . If no R-RTS/R-CTS is received or time T is expired, the SU_s participates in the reservation process. Otherwise, it will defer and wait for the notification from the transmission pair or a timeout. Whenever there is at least one packet buffered in the queue, SU_s sends reservation requirement to SU_d . Upon receiving the requirement, SU_d will reply and other SUs overhearing these message exchanging cease their own sensing, and wait for the notification from this transmission pair or a timer expiration. When the sensing or cooperative sensing is finished, other neighboring SUs start a new round of competition for the control channel with a random backoff.

B. Sensing

After reserving the data channel, SU_s and SU_d start to sense the spectrum channel. In this phase, we use S-RTS/S-CTS packets for spectrum sensing and negotiation between SU_s and SU_d . In order to indicate the mechanism of our scheme, the C-RTS/C-CTS packets are included in the RTS/CTS model for SU_c to acknowledge its participation. Fig. 1 shows the flowchart of the sensing procedure of the source node SU_s . Fig. 2 shows the flowchart of the sensing procedures of SU_c and SU_d . In particular, we provide the detailed description as follows.

Source SU (SU_s)

1) SU_s senses the channel to judge the availability of the channel. If the channel is not occupied by a PU, SU_s sends an S-RTS packet to SU_d , including the availability information of the detected channel. Otherwise, SU_s sends the channel unavailability information to SU_d .

2) If an S-CTS packet from SU_d is not heard after a CTS timer, SU_s should perform a random backoff, as if it encounters a collision. If SU_s receives the information of channel availability from SU_d , SU_s and SU_d will start the transmission phase (please refer to Section III.C). If SU_s receives the information of channel unavailability from SU_d , SU_s will send C-RTS to the neighborhood of SU_c and SU_d .

3) If SU_s does not receive any feedback from SU_c , it then sends cooperation requirement again after a random backoff. If the feedback is successfully received, SU_s counts the number of SU_c according to the SU-selecting algorithm (please refer to Section IV). When the number of SU_c s satisfies the requirement of the cooperative sensing, SU_s stops sending cooperation requirement to the neighborhood of SU_c and divides the chosen SU_c s into a number of teams.

4) SU_s sends the cooperative information to the SU_c s and then join the cooperative sensing with SU_c s. Such information includes grouping information and the specific channels.

5) Upon receiving the sensing results, SU_s should declare the success of spectrum sensing and return to 1). Otherwise, SU_s should perform a random backoff, and return to 4).

Cooperative SU (SU_c)

1) Upon receiving the cooperation requirement, SU_c sends feedback to the source node SU_s and waits for the cooperative information.

2) If the information for the cooperation is not received after a CTS timer, SU_c assumes that the information is lost and then reverts to the original state. Otherwise, SU_c starts the channel sensing based on the cooperative information.

3) After the time duration t_s , SU_c determines the PU's activity on the detected channel and sends cooperation acknowledgement to SU_s with the sensing result.

Destination SU (SU_d)

1) SU_d senses the same channel with SU_s in a synchronous way. After the sensing time t_s , SU_d makes the final decision about the state (ON/OFF) of the channel, and waits for the sensing requirement from the source node SU_s .

2) If the destination node SU_d receives the sensing requirement with the sensing result from the source node SU_s , it delivers the sensing result back to SU_s . If the sensing result indicates that the channel is available, SU_d is ready for receiving data. Otherwise, SU_d waits for the cooperation requirement.

3) If cooperation requirement is received, SU_d will join the cooperative sensing and report the sensing results to SU_s . Then, SU_d returns to 2). If neither a sensing nor an cooperation requirement is heard after a timer, SU_d will go back to the initial state.

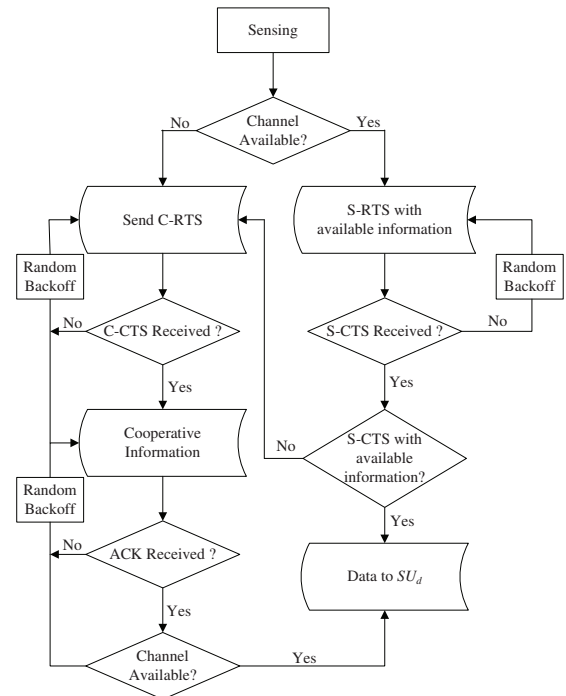


Fig. 1. The sensing work flow of SU_s .

C. Transmission

After the source node SU_s and the destination node SU_d successfully find an available channel, they begin to use the channel to transmit data packets. Here, we use the T-RTS/T-CTS pair to indicate the transmission process. Before

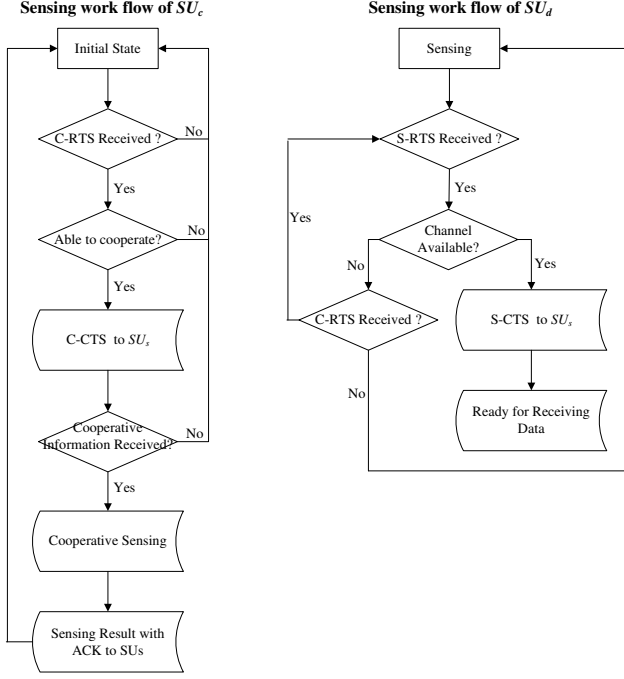


Fig. 2. The sensing work flow of SU_c and SU_d .

starting the transmission, SU_s will send T-RTS to SU_d for declaring the beginning of transmission. Upon receiving this requirement, SU_d replies T-CTS. If this feedback is received, SU_s sends the data packets to SU_d and sets acknowledgment timeout. When the acknowledgment from SU_d arrives, SU_s should declare the transmission success over the control channel. This success information ends the deferring of the neighboring SUs and starts a new round of reservation. If acknowledgment is not received after an acknowledgment timeout, SU_s should perform a random backoff and retransmit the data packets.

IV. REDUCING SENSING OVERHEAD VIA SU-SELECTING ALGORITHM

In this section, we would like to reduce the sensing overhead by introducing an SU-selecting algorithm. In this algorithm, we employ the alternative pattern and the channel data rate of the SUs' used channel as the cooperative SU's selection conditions.

A. Channel Pattern for SUs

Each channel alternates between state ON and state OFF which is depending on the PUs' usage pattern. The channel that an SU uses may be busy after a period τ based on the previous idle status. During the busy period, the SUs are not allowed to access the channels which are occupied by a PU. In this case, if these SUs are selected for cooperative sensing, the overhead of cooperation can be substantially reduced since sensing overhead is mainly incurred by ceasing transmissions during the cooperative sensing period. Let $I_\epsilon \in \{0, 1\}$ represents the binary channel state of channel ϵ . $I_\epsilon = 1$ refers to state ON and $I_\epsilon = 0$ refers to state OFF. Let $P_{I_\epsilon 1}(\tau)$ denotes

the transition probability that the ϵ th channel will be busy after τ seconds with the initial state I_ϵ . We can express the transition probability $P_{01}(\tau)$ from channel state OFF to ON as [28]

$$P_{01}(\tau) = p - pe^{-(\mu_{OFF} + \mu_{ON})\tau} \quad (3)$$

where p is the channel availability.

It is shown that the $P_{01}(\tau)$ only relate with the most recent channel state $I_\epsilon = 0$ and τ , the time between the most recent sensing and the current sensing. Considering that τ is different among the channels, then $P_{01}(\tau)$ is accordingly different with distinct SUs. In order to reduce the sensing overhead, our goal is to select the cooperative SUs with the high $P_{01}(\tau)$. In the following section, we first present the optimal SUs-selecting algorithm in the time-invariant channel case. Then, we derive the optimal selecting algorithm for the case where the channel has time-varying feature.

B. SU-Selecting Algorithm

1) *Time-Invariant Channel Case:* A channel may stay at the idle state after τ seconds. The sensing overhead is expected to be high if the SUs who used these channels are chosen for cooperative sensing. Thereafter, in order to reduce sensing overhead, we select the cooperative SUs in the descending order of the probability $P_{01}(\tau)$. We can present the SU-selecting algorithm as follows.

- 1) SU_s delivers the Cooperative Sensing Request message (MSG-CSR) to the neighboring SU_{cs} when a PU's activity is detected on a channel.
- 2) The k th SU_c calculates $P_{01}(\tau_k)$ where τ_k represents the time duration from the moment of the most recent sensing to the moment of receiving MSG-CSR.
- 3) SU_s selects the cooperative SU_{cs} according to the descending order of $P_{01}(\tau_k)$.

The probability $P_{00}(\tau_k)$ can be alternatively employed since $P_{00}(\tau_k) = 1 - P_{01}(\tau_k)$. Hence, the SU-selecting algorithm can obtain the same strategy if we choose the cooperative SUs in the ascending order of the probability $P_{00}(\tau_k)$.

2) *Time-Varying Channel Case:* To reduce the sensing overhead, the SUs which have the highest $P_{01}(\tau)$ should be selected for cooperation in the time-invariant channel case. Here, the probability $P_{01}(\tau)$ represents the transition probability from state OFF to state ON. However, this strategy may not be efficient in the time-varying case where the channel data rate changes over the time. We choose the SUs not only based on the probability $P_{01}(\tau)$ but also based on the channel data rate of their used channels. The SUs' used channels which have both the lowest channel data rate and the highest $P_{01}(\tau)$ (or lowest $P_{00}(\tau)$) are selected to perform sensing and search the available channels. As a consequence, in the time-varying channel case, the SU-selecting algorithm can be provided as follows.

- 1) SU_s delivers the Cooperative Sensing Request message (MSG-CSR) to the SU_{cs} when PU's activity is detected on a channel.
- 2) The k th SU_c calculates $P_{00}(\tau_k)$, where τ_k represents the time duration from the moment of the most recent

sensing to the moment of receiving the message MSG-CSR.

- 3) SU_s multiplies $P_{00}(\tau_k)$ by the channel data rate R_k of the k th SU's channel.
- 4) SU_s selects the cooperative SUs according to the ascending order of $P_{00}(\tau_k)R_k$.

V. ANALYSIS AND OPTIMIZATION FOR THE SATURATION NETWORKS

In this section, we will analyze the sensing overhead and throughput in a saturation networks. Our objective is to find two key design parameters: the number of cooperative teams and the number of SUs in one team. In a saturation network, we consider the CR network consisting of C licensed channels and K number of SUs. The set of licensed channels is denoted as $\mathbf{C} \equiv \{1, 2, \dots, C\}$ with $|\mathbf{C}| = C$. The set of SUs is denoted as $\mathbf{K} \equiv \{1, 2, \dots, K\}$ with $|\mathbf{K}| = K$. We allow the cooperative sensing scheme to choose a certain number of SUs which are further divided into U teams. Each team has q ($q \geq 1$) number of SUs and is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U and q satisfies $Uq \leq K$.

A. Time-Invariant Channel Case

1) *Sensing Overhead*: We define T_s as the total time duration spent by the k th cooperative SU after n_s number of the cooperative sensing. With the proposed group-based sensing strategy, up to U number of channels can be detected in one sensing period. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing and the variable n_s varies between 1 and $\lceil C/U \rceil$. If the channels can be found after n_s number of cooperative sensing, the cooperative SUs can not transmit any packets during $T_s = n_s t_s$ sensing periods. This operation is unfortunately unavoidable in the cooperative sensing. Let o_k^{TI} denotes the sensing overhead caused by the k th cooperative SU in the time-invariant situation. Then, we have

$$o_k^{TI} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (4)$$

where R_k denotes the channel data rate of the channel used by the k th cooperative SU. Since the channel data rate is a constant in the time-invariant channel case, we obtain sensing overhead as

$$o_k^{TI} = \int_0^{T_s} R P_{00}(\tau_k) d\tau_k. \quad (5)$$

2) *Throughput*: Let P_s represents the probability that a channel is successful found. This is equal to the probability that a channel is available and no false alarm is generated by q number of cooperative SUs. Then, we have $P_s = p[1 - P_f(q)]$, where p is the channel availability and $P_f(q)$ is given by (2). Let u denotes the number of available channels that are found in a cooperative sensing. The probability distribution function of the random variable u is given by $\binom{U}{u}(1-P_s)^{U-u}P_s^u$. Then, we can obtain the probability, $P_{av,1}^{TI}$,

that the available channels can be found in one cooperative sensing as

$$P_{av,1}^{TI} = \sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u. \quad (6)$$

With the proposed group-based sensing strategy, up to U number of channels can be detected in one sensing period. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. We can then obtain the probability P_{av,n_s}^{TI} that an available channel is found after n_s cooperative sensing.

$$P_{av,n_s}^{TI} = (1 - P_{av,1}^{TI})^{n_s-1} P_{av,1}^{TI}. \quad (7)$$

Let T_r denotes the average transmission time for an SU using discovered available channel. We can derive the throughput of an SU by using this channel as follows

$$\begin{aligned} \mathcal{T}^{TI} &= \sum_{n_s=1}^{\lceil C/U \rceil} P_{av,n_s}^{TI} T_r R \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} T_r R \left[1 - \sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u \right]^{n_s-1} \\ &\quad \times \left[\sum_{u=1}^U \binom{U}{u} (1-P_s)^{U-u} P_s^u \right] \end{aligned} \quad (8)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

To determine the optimal value of U and q , we introduce a new term *the achievable throughput*, which is defined as the difference between sensing overhead and throughput. It is clear that the achievable throughput is able to demonstrate the purely achieved throughput after removing the penalty with respect to sensing overhead. For this perspective, the concept is able to capture the inherent tradeoff in the cooperative sensing.

Suppose that the available channel is discovered at the n_s th detection by U number of teams. We can obtain the total sensing overhead \mathcal{O}^{TI} ,

$$\mathcal{O}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s P_{av,n_s}^{TI} q U o_k^{TI}. \quad (9)$$

Our objective is to find the optimal U and q for the group sensing in order to maximize the achievable throughput. The optimization problem is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{TI} = \mathcal{T}^{TI} - \mathcal{O}^{TI} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}, \end{aligned} \quad (10)$$

where $P_{f,th}$ and $P_{d,th}$ represent the threshold of the false alarm probability and detection probability, respectively. Based on the derived expression of \mathcal{T}^{TI} and \mathcal{O}^{TI} , the optimal number of cooperative teams and SUs in one team can be determined by solving (10). Considering the prohibitively high complexity of the optimization problem, we have resorted to numerical methods to find the optimal result to maximize the achievable throughput.

B. Time-Varying Channel Case

In this section, we will perform an analytical analysis on sensing overhead and throughput in the time-varying channel case. It is noteworthy that the analysis in the time-varying channel case is not a trivial extension of the analysis in the time-invariant channel case. On the one hand, the analysis in the time-invariant channel case is necessary to provide an easy understanding of the SUs cooperation behavior; and also the inherent trade-off between throughput and sensing overhead. On the other hand, the time-varying channel case is much more complicated than the time-invariant case by considering the complex channel dynamics. The development of sensing overhead and throughput is dependent on the channel dynamics, which leads to new equations for channel data rate, sensing overhead, throughput and hence achievable throughput in the time-varying case.

1) *Sensing Overhead*: Based on the SU-selecting algorithm, we can analyze the sensing overhead caused by the group-based sensing under the time-varying channel case. Let $\bar{R} = [R_1, R_2, \dots, R_M]$ represents the channel data rate vector of length M . Without loss of generality, we suppose $R_1 < R_2 < \dots < R_M$. Let $\bar{X} = [X_1, \dots, X_K]$ be a random sample from \bar{R} of length K . Hereby, the vector \bar{X} represents the specific value of a parallel sensing and hence has length K instead of M . Let $X_k (k \in \mathbf{K})$ denotes the k th order statistics of the sample. Employing order statistics theory [30], we can derive the probability $\Pr\{X_k = R_n\} (k \in \mathbf{K}; n \in \mathbf{M})$ which shows that the k th SU's channel data rate is equal to R_n . We suppose that there are $(h-1)$ number of samples in \bar{X} with the probability $\Pr\{X_i < R_n\} (1 \leq i \leq h-1; 1 \leq h \leq k)$; $(l-h+1)$ number of samples in \bar{X} with the probability $\Pr\{X_i = R_n\} (1 \leq i \leq l-h+1; k \leq l \leq K)$; and $(n-l)$ number of samples in \bar{X} with the probability $\Pr\{X_i > R_n\} (1 \leq i \leq n-l)$.

The random variables X_i are statistically independent and identically distributed with the generic form X , we have

$$\Pr\{X < R_n\} = \sum_{R_i < R_n} \Pr\{X = R_i\} = \sum_{i=1}^{n-1} \pi_i.$$

Since the $(h-1)$ samples could be any random samples from \bar{X} , we obtain the probability of this case $\binom{K-h+1}{h-1} (\sum_{i=1}^{n-1} \pi_i)^{h-1}$.

For the probability $\Pr\{X_i = R_n\}$, we have

$$\Pr\{X = R_n\} = \pi_n.$$

Since the number of $(l-h+1)$ samples could be any random samples from the rest of $(K-h+1)$ samples of X , we obtain the probability of this case as $\binom{K-h+1}{l-h+1} (\pi_n)^{l-h+1}$.

$$\begin{aligned} \Pr\{X_i > R_n\} &= 1 - \Pr\{X \leq R_n\} \\ &= 1 - \sum_{R_i < R_n} \Pr\{X = R_i\} \\ &= 1 - \sum_{i=1}^n \pi_i. \end{aligned}$$

Similarly, we obtain the probability of this condition as $\binom{K-l}{K-l} (1 - \sum_{i=1}^n \pi_i)^{K-l}$. By summarizing all possibilities, the probability $\Pr\{X_k = R_n\}$ is given by (13). Then, the channel

data rate of the selected SU, denoted as $R_k (k \in \mathbf{K})$, is given by

$$R_k = \sum_{n=1}^M \sum_{i=1}^n R_i \Pr\{X_k = R_n\}. \quad (11)$$

Let o_k^{TV} denotes the sensing overhead caused by the cooperative SU $_k$ after n_s number of cooperative sensing under the time-varying channel condition. We can obtain

$$o_k^{TV} = \int_0^{T_s} R_k P_{00}(\tau_k) d\tau_k \quad (12)$$

where $T_s = n_s t_s$ denotes the time spent by the k th cooperative SU after n_s number of sensing.

2) *Throughput*: Let v represents the number of spectrum channels that are found in a cooperative sensing. The probability density function (PDF) of the random variable v is given by $\binom{U}{v} (1 - P_s)^{U-v} P_s^v$ where P_s is given by (1). Let P_{av}^{TV} denotes the probability that an available channel can be found in one cooperative sensing in the time-varying channel case. Then, we have

$$P_{av}^{TV} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v. \quad (14)$$

We need to find the available channel with the highest channel data rate by the U teams. We will select the channel that has the highest channel data rate in these v channels for the SU to access. Let $R_m (1 \leq m \leq M)$ denotes the highest channel rate in these v number of channels. It is noteworthy that the subscript m in R_m represents the index of channel data rate, which ranges from 1 to M . Let $P_{rate,v}$ denotes the probability that there are channels whose maximum rate is no lower than $R_m (1 \leq m \leq M)$ in the founded v channels. Then, we have

$$P_{rate,v} = \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right]. \quad (15)$$

Conditioning on all possibilities on the random variable v , we obtain the probability P_{rate} that there are channels whose maximum rate is no lower than $R_m (1 \leq m \leq M)$

$$P_{rate} = \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v P_{rate,v}. \quad (16)$$

We obtain the probability $P_{maxrate}$ that R_m is the maximal channel data rate from all discovered available channels.

$$P_{maxrate} = (1 - P_{av}^{TV})^{n_s-1} P_{rate}. \quad (17)$$

With the proposed sensing strategy, each sensing period may find up to U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods.

$$\begin{aligned} \Pr\{X_k = R_n\} &= \sum_{l=k}^K \sum_{h=1}^k \left[\binom{K}{h-1} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} \binom{K-h+1}{l-h-1} (\pi_n)^{l-h+1} \binom{K-l}{K-l} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right] \\ &= \sum_{l=k}^K \sum_{h=1}^k \left[\frac{K!}{(h-1)!(l-h+1)!(K-1)!} \left(\sum_{i=1}^{n-1} \pi_i \right)^{h-1} (\pi_n)^{l-h+1} \left(1 - \sum_{i=1}^n \pi_i \right)^{K-l} \right]. \end{aligned} \quad (13)$$

We can derive throughput of the SU by using this channel as

$$\begin{aligned} \mathcal{T}^{TV} &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{maxrate} T_r R_m \\ &= \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M T_r R_m (1 - P_{av}^{TV})^{n_s-1} \\ &\quad \sum_{v=1}^U \binom{U}{v} (1 - P_s)^{U-v} P_s^v \left(\sum_{i=1}^m \pi_i \right)^v \left[1 - \left(\sum_{i=1}^{m-1} \pi_i \right)^v \right] \end{aligned} \quad (18)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

We formulate the achievable throughput optimization problem by considering both throughput and sensing overhead in the time-varying channel condition. The total sensing overhead \mathcal{O}^{TV} is given by

$$\mathcal{O}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} n_s q U P_{av}^{TV} o_k^{TV}. \quad (19)$$

Consequently, the achievable throughput maximization problem in the time-varying channel case is formulated as

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}^{TV} = \mathcal{T}^{TV} - \mathcal{O}^{TV} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}, \end{aligned} \quad (20)$$

where \mathcal{T}^{TV} and \mathcal{O}^{TV} are given by (18) and (19), respectively. By solving (20), we can find the optimal U and q for the group sensing in order to maximize the achievable throughput.

VI. ANALYSIS AND OPTIMIZATION FOR THE NON-SATURATION NETWORKS

In this section, we will derive the sensing overhead and throughput in the non-saturation networks. Suppose that an SU may have an empty queue. In this network, we consider a discrete-time queue with an infinite capacity buffer for the queuing behavior of an SU. The packets arrival of the SUs is assumed to be a Poisson process with arrival rate λ_{pac} . The packets are served on a First-In First-Out (FIFO) basis. The service time of each packet is modeled as identically distributed nonnegative random variables, denoted as $\chi_n (n \geq 1)$, whose arrival process is independent to each another. The similar assumption has been frequently used in the literature, e.g [14], [29]. Let $F(t)$ denotes the service time Cumulative Distribution Function (CDF) with mean $0 < 1/\mu = \int_0^\infty t dF(t)$. Let ρ represents the traffic

load and it is given by $\rho = \frac{\lambda_{pac}}{\mu}$. For a practical system, the traffic load is less than 1, i.e. $\rho < 1$.

Similar to saturation network, we still consider the CR network consisting of C licensed channels and K number of SUs. The cooperative SUs are divided into U teams. Each team has q ($q \geq 1$) number of SUs. Each team is assigned to sense a distinct channel during each sensing period t_s . The relationship among the variables K , U and q also satisfies $Uq \leq K$. Next, we will formulate the throughput maximization problem with time-invariant and time-varying channel, respectively.

A. Time-Invariant Channel Case

Since the channel data rate will not change with the time in time-invariant channel case. The packet service time is a constant, which means we are able to employ the single-server queuing model, $M/D/1$, to evaluate the group sensing scheme with time-invariant channel.

Based on the result of [30], the variance of service time $E(\chi^2) = 0$ in the $M/D/1$ model. Let \bar{N}_q^{TI} denotes the average number of packets in a queue for time-invariant channel case. Then, we have

$$\bar{N}_q^{TI} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\rho^2}{2(1-\rho)}. \quad (21)$$

1) *Sensing Overhead*: To reduce the sensing overhead, we still select qU SUs that have the lowest channel data rate and least $P_{00}(t)$ among K SUs in the non-saturation network. As explained, each group sensing can sense U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of group sensing. Let N_{sense}^{TI, n_s} be the total number of packets that can be transmitted in the n_s number of group sensing by the qU sensing SUs if they are not participating the group-based cooperative sensing. N_{sense}^{TI, n_s} is given by

$$N_{sense}^{TI, n_s} = \min \left\{ n_s q U \bar{N}_q^{TI}, (q U T_s R_{use})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (22)$$

where R_{use} denotes the channel data rate of the using channel, l denotes the length of a packet, $T_s = t_s n_s$ and \bar{N}_q^{TI} is given by (21).

Suppose that the available channel is discovered at the n_s th detection by U number of teams in non-saturation network. Then, in a time-invariant channel case, we can obtain the total sensing overhead $\mathcal{O}_{nonsat}^{TI}$,

$$\mathcal{O}_{nonsat}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av, n_s}^{TI} N_{sense}^{TI, n_s} l \quad (23)$$

where P_{av,n_s}^{TI} is given by (7).

2) *Throughput*: Let T_r denotes the average transmission time for an SU using discovered available channel. In the time-invariant channel case, the average number of packets that SUs send during T_r at the equilibrium state is given by

$$N_D^{TI} = \min \left\{ \bar{N}_q^{TI}, (T_r R_{use})/l \right\} \quad (24)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

With the proposed sensing strategy, each sensing period may find up to U number of channels. Hence, all channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. Hence, we can derive the throughput of an SU by using the discovered available channel as follows.

$$\mathcal{T}_{nonsat}^{TI} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av,n_s}^{TI} N_D^{TI} l \quad (25)$$

where the item P_{av,n_s}^{TI} is given by (14).

In terms of the achievable throughput maximization, we formulate the following problem

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{nonsat}^{TI} = \mathcal{T}_{nonsat}^{TI} - \mathcal{O}_{nonsat}^{TI} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}. \end{aligned} \quad (26)$$

B. Time-Varying Channel Case

Considering the time-varying channel case, the channel data rate may vary from time slot to time slot. This alternative indicates that an SU's capacity is a random variable. Following this reasoning, we can use the M/G/1 queuing model.

1) *Sensing Overhead*: Since the service time of each packets depends on the channel data rate, we can express the CDF $F(t)$ as

$$F(t) = l/R_i(t) \quad (27)$$

where $R_i(t)$ denotes the channel data rate of the i th channel state at the t th time slot. Let \bar{N}_q^{TV} denotes the average number of packets in a queue for time-varying channel case. Then, we have

$$\bar{N}_q^{TV} = \sum_{v=1}^{\infty} v p_{v+1} = \frac{\lambda^2 E(\chi^2) + \rho^2}{2(1-\rho)} \quad (28)$$

where $E(\chi^2) = \int_0^\infty t^2 dF(t)$.

In the time-varying channel case, let N_{sense}^{TV,n_s} be the total number of packets that can not be transmitted by the qU cooperative SUs in n_s number of group sensing. N_{sense}^{TV,n_s} is given by

$$N_{sense}^{TV,n_s} = \min \left\{ n_s q U \bar{N}_q^{TV}, (q U T_s R_{use})/l \right\}; 1 \leq n_s \leq \lceil C/U \rceil \quad (29)$$

where $T_s = t_s n_s$ and \bar{N}_q^{TV} is given by (28).

Then, in a time-varying channel case, the total sensing overhead for discovering an available channel can be obtained as follows

$$\mathcal{O}_{nonsat}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} P_{av}^{TV} N_{sense}^{TV,n_s} l. \quad (30)$$

2) *Throughput*: We use T_r to denote the average transmission time for an SU using discovered available channel in the time-varying channel case. Then, the average number of packets that SUs send during T_r is given by

$$N_D^{TV} = \min \left\{ \bar{N}_q^{TV}, (T_r R_{use})/l \right\} \quad (31)$$

where $T_r = \int_0^\infty \mu_{OFF} e^{-\mu_{OFF} t} dt = 1/\mu_{OFF}$.

The proposed sensing strategy may find up to U number of channels during each sensing period. All channels can be sensed completely within $\lceil C/U \rceil$ number of sensing periods. Suppose that the available channel can be found after n_s number of group sensing, we can obtain the throughput of an SU by using discovered available channel in the time-varying channel case.

$$\mathcal{T}_{nonsat}^{TV} = \sum_{n_s=1}^{\lceil C/U \rceil} \sum_{m=1}^M P_{maxrate} N_D^{TV} l \quad (32)$$

where the item $P_{maxrate}$ is given by (17).

Finally, we formulate the following problem in terms of achievable throughput maximization

$$\begin{aligned} \max_{q,U} \quad & \mathcal{G}_{nonsat}^{TV} = \mathcal{T}_{nonsat}^{TV} - \mathcal{O}_{nonsat}^{TV} \\ \text{s.t.} \quad & qU \leq K, \\ & P_f(q) \leq P_{f,th}, \quad P_d(q) \geq P_{d,th}. \end{aligned} \quad (33)$$

Considering the complexity of the optimization problems, we still use numerical methods to find the optimal result to maximize the achievable throughput in non-saturation network. The optimal results are provided in the following section under time-invariant and time-varying channel condition, respectively.

VII. SIMULATION RESULTS

In this section, we demonstrate the performance of the proposed GC-MAC in CR networks. The network consists of total $C = 10$ licensed channels. The channel parameter of the OFF period $\mu_{OFF} = 1/100$. We concentrate on the low SNR situation, the SNR threshold for a PU at the tagged SU is $\gamma = -10dB$. The channel bandwidth is 1 MHz and the target probability of detection $P_d = 0.9$ which is a important parameter used by 802.22 standard [31]. The length of RTS/CTS packets and sensing period are 40Bytes and 1ms, respectively. Considering the time-varying channel case, the number of channel data rate state is $M = 10$. Accordingly, the channel data rate of each channel ranges between $0.1MB/s - 1MB/s$, which decreases or increases its value by 10(%) once every 5ms.

Table.I shows the impacts of the number of cooperative teams and the number of SUs in one team on the achievable saturation throughput in the time-invariant channel situation. In these examples, the channel availability p is set as 1/2. We can determine the optimal achievable throughput by choosing appropriate parameters. From Table.I, we observe that the achievable throughput is maximized as 0.9822. In the time-varying channel case, Table.II shows the achievable saturation throughput that the maximal value is 0.8154. The saturation

TABLE I
THE ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATION OF U AND j IN TIME-INVARIANT CHANNEL CASE.

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.9422	0.9365	0.9428	0.9359	0.9162	0.9208	0.9184	0.9126	0.9050	0.8746
$q=2$	0.9631	0.9822	0.9376	0.9061	0.8635	—	—	—	—	—
$q=3$	0.9616	0.9151	0.8797	—	—	—	—	—	—	—
$q=4$	0.9366	0.8708	—	—	—	—	—	—	—	—
$q=5$	0.9059	0.8454	—	—	—	—	—	—	—	—
$q=6$	0.8887	—	—	—	—	—	—	—	—	—
$q=7$	0.8712	—	—	—	—	—	—	—	—	—
$q=8$	0.8527	—	—	—	—	—	—	—	—	—
$q=9$	0.8347	—	—	—	—	—	—	—	—	—
$q=10$	0.8163	—	—	—	—	—	—	—	—	—

TABLE II
THE ACHIEVABLE SATURATION THROUGHPUT WITH DIFFERENT COMBINATION OF U AND j IN TIME-VARYING CHANNEL CASE.

Achievable Throughput	$U=1$	$U=2$	$U=3$	$U=4$	$U=5$	$U=6$	$U=7$	$U=8$	$U=9$	$U=10$
$q=1$	0.7839	0.7798	0.7764	0.7713	0.7645	0.7600	0.7544	0.7483	0.7421	0.7341
$q=2$	0.7907	0.8154	0.7282	0.7935	0.7245	—	—	—	—	—
$q=3$	0.7864	0.7730	0.7515	—	—	—	—	—	—	—
$q=4$	0.7804	0.7571	—	—	—	—	—	—	—	—
$q=5$	0.7731	0.7474	—	—	—	—	—	—	—	—
$q=6$	0.7681	—	—	—	—	—	—	—	—	—
$q=7$	0.7630	—	—	—	—	—	—	—	—	—
$q=8$	0.7681	—	—	—	—	—	—	—	—	—
$q=9$	0.7525	—	—	—	—	—	—	—	—	—
$q=10$	0.7472	—	—	—	—	—	—	—	—	—

throughput in the time-varying case is lower than that in the time-invariant case. This is expected since the channel data rate may be reduced in the time-varying condition due to fading and signal variation. Similarly, we can obtain the maximal non-saturation throughput in the time-invariant channel case and the time-invariant channel case as 0.9107 and 0.8095, respectively.

A. Achievable Throughput

We compare our GC-MAC which uses group-based cooperative sensing scheme (GCSS) with accuracy priority cooperative sensing scheme (ACSS) [12] and efficiency priority cooperative sensing scheme (ECSS) [14]. In the scheme ACSS, every cooperative SU monitors a single channel during each sensing period. The main focus of this scheme is to improve sensing accuracy of a PU's activity. In the scheme SCSS, the cooperative SUs are assigned to sense different channels simultaneously for the sensing efficiency enhancement. This sensing operation assumes that the sensing of each channel by a single SU is accurate, which however may be difficult to achieve in practical CR networks.

1) *Time-Invariant Channel Case*: Fig. 3 shows the throughput comparison among GCSS, ACSS and ECSS in the time-invariant channel case when $p = 2/3$ and $1/2$. In this example, the sensing accuracy requirement is set as $P_{f,th} = 0.05$. It is observed that the achievable throughput in all three schemes increases with higher channel availability p , which is intuitively understandable. The result indicates that GCSS is able to achieve much higher throughput than ACSS and ECSS. This is because GCSS is able to search and find more spectrum opportunities. When the number of the cooperative SUs becomes larger, there is higher chance to find the available channels which leads to less sensing overhead. In addition,

ECSS uses all SUs to sense different channels, which causes a less sensing accuracy of single channel and leads to lower throughput. Comparatively, the proposed GCSS chooses the optimal number of teams and the number of SUs in each team. In this case, sensing overhead is significantly reduced and throughput increases. As a consequence, our proposed GCSS is able to achieve high sensing efficiency with low sensing overhead.

Fig.4 shows the non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-invariant channel case when $p = 2/3, 1/2$. Again, the $P_{f,th} = 0.05$ is assumed as 0.05. It can be observed that, GCSS substantially outperforms the other two schemes. In addition, we notice that it will obtain higher throughput if the channel availability p becomes larger.

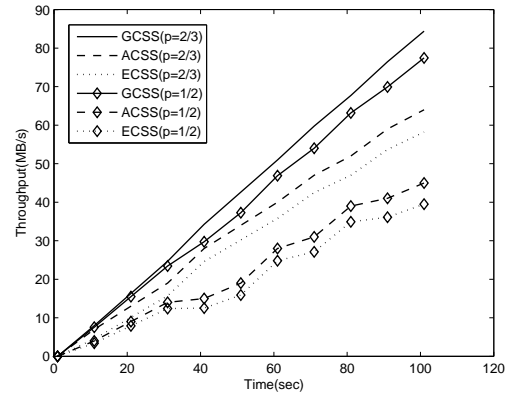


Fig. 3. The saturation throughput in the time-invariant channel case with different p .

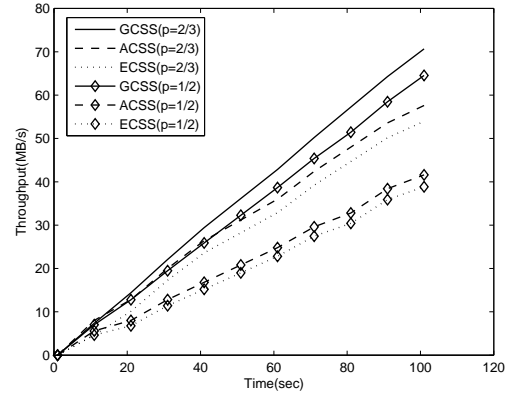


Fig. 4. The non-saturation throughput in the time-invariant channel case with different p .

2) *Time-Varying Channel Case*: Fig.5 and Fig.6 show the saturation and non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-varying channel case when $p = 2/3, 1/2$ and $P_{f,th} = 0.05$. The comparison indicates that GCSS is able to achieve higher throughput than ACSS and ECSS. This is because GCSS is able to detect and find more spectrum opportunities even when the channel

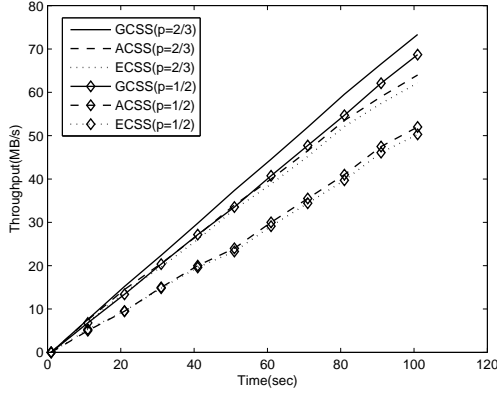


Fig. 5. The saturation throughput in the time-varying channel case with different p .

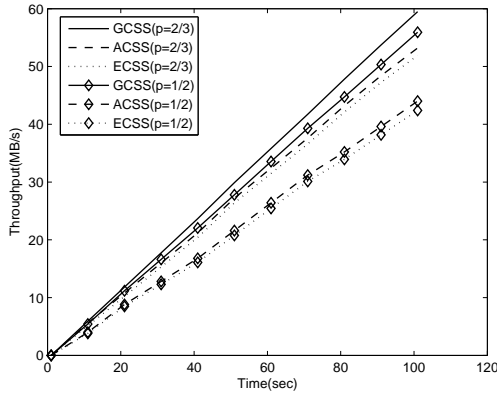


Fig. 6. The non-saturation throughput in the time-varying channel case with different p .

is dynamic. When the number of cooperative SUs becomes larger, our scheme not only finds the available channel quicker but also chooses the channel with maximal rate if more than one available channels are found. Moreover, with the comparison to ECSS, GCSS has the advantage of reducing sensing overhead. As a consequence, the proposed GCSS achieves higher throughput in the time-varying channel case.

In addition, we illustrate the achievable throughput comparison among GCSS, ACSS and ECSS under the complex-valued signal model. Fig.7 and Fig.8 show the saturation and non-saturation throughput comparison among GCSS, ACSS and ECSS in the time-varying channel case, respectively. We observe that GCSS also can obtain higher throughput than that in ACSS and ECSS. This observation indicates the effectiveness of our proposed MAC protocol in both of the real-valued and complex-valued signal model.

B. Sensing Overhead

1) *Time-Invariant Channel Case*: Fig.9 shows sensing overhead among GCSS, ACSS and ECSS in the time-invariant channel case for saturation situation. It is observed that GCSS generates the lowest sensing overhead. This can be explained as follows. GCSS selects the SUs to cooperate

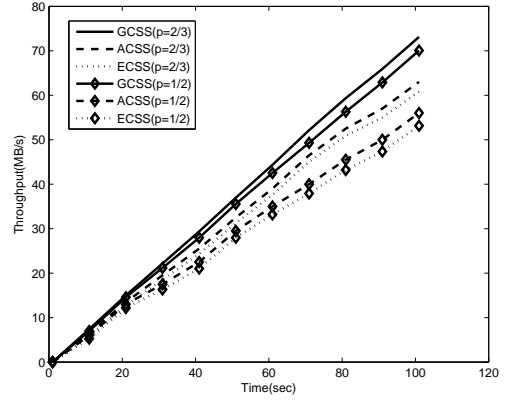


Fig. 7. The saturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

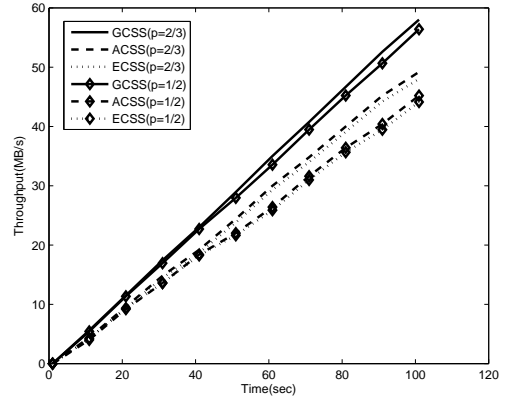


Fig. 8. The non-saturation throughput comparison under complex-valued signal system in the time-varying channel case with different p .

by using the SU-selecting algorithm. The algorithm chooses the SUs with low channel available probability (P_{00}) for the cooperative sensing. This operation can substantially reduce sensing overhead by avoiding the temporary stopping of the ongoing transmissions when their channels are occupied by PUs. Comparatively, ACSS and ECSS have no similar mechanisms and hence generate higher sensing overhead. Fig.10 shows the sensing overhead for non-saturation situation. Similar observations and conclusions can be made. In addition, we notice that sensing overhead decreases when the channel availability p becomes larger. With more channel availability, there are more chances to find spectrum opportunities in a fixed period; and hence less sensing overheads.

2) *Time-Varying Channel Case*: Considering the time-varying channel case, Fig.11 and Fig.12 show the sensing overhead with different channel availability p under saturation and non-saturation situation, respectively. It is clear that sensing overhead becomes lower when the channel availability p increases. Again, the proposed GCSS incurs lower sensing overhead than ACSS and ECSS. With the time-varying channel, we have considered the channel dynamics and rate variation in selecting appropriate SUs to perform sensing. Following this way, sensing overhead in traditional cooperative

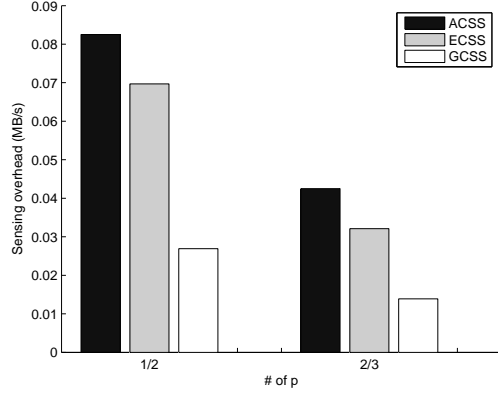


Fig. 9. The sensing overhead in the time-invariant channel case with different p for saturation situation.

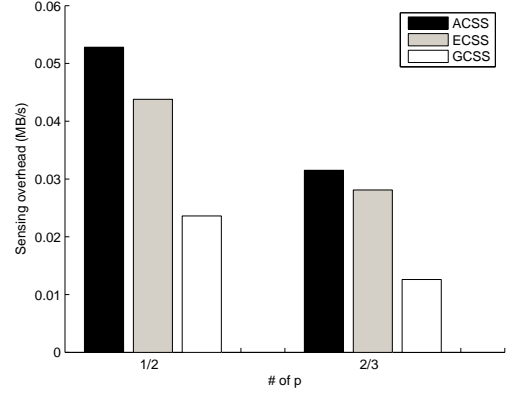


Fig. 12. The sensing overhead in the time-varying channel case with different p for non-saturation situation.

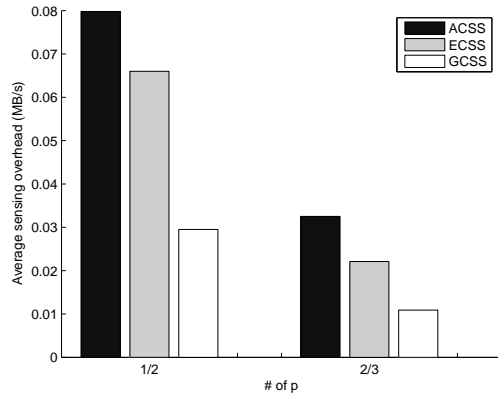


Fig. 10. The sensing overhead in the time-invariant channel case with different p for non-saturation situation.

sensing can be partially avoided.

VIII. CONCLUSION

We design an efficient MAC protocol with selective grouping and cooperative sensing in cognitive radio networks. In our

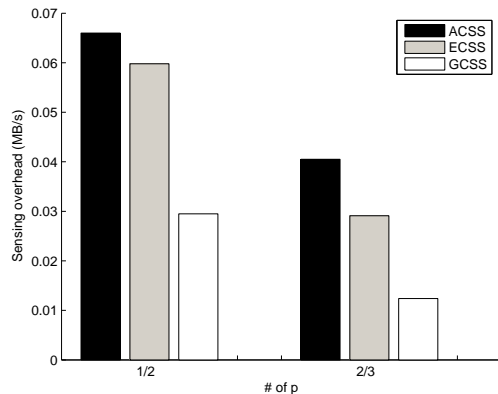


Fig. 11. The sensing overhead in the time-varying channel case with different p for saturation situation.

protocol, the cooperative MAC can quickly discover the spectrum opportunities without degrading sensing accuracy. An SU-selecting algorithm is proposed for specifically choosing the cooperative SUs in order to substantially reduce sensing overhead in both time-invariant and time-varying channel cases. We formulate the throughput maximization problems to determine the crucial design parameters and to investigate the trade-off between sensing overhead and throughput. Simulation results show that our proposed protocol can significantly reduced sensing overhead without degrading sensing accuracy.

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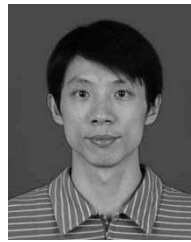
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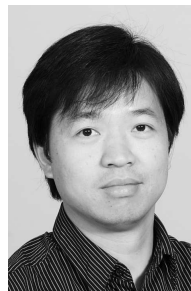


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